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Loss of Vision from High Intensity Light

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

LOSS OF VISION FROM HIGH INTENSITY LIGHT

FOREWORD

The following collection of papers represents a large part of the total program of a symposium held in Paris in March 1966.

Some papers of a classified nature have been omitted from this publication. The published papers represent the recent opinions of experts who have for a number of years been associated with this problem area, and it is hoped that bringing them together in one volume may be useful to the many individuals and organisations interested in the various facets of the problem.

T. C. D. WHITESIDE

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RETINAL EFFECTS

VISUAL DECREMENT IN HUMANS FOLLOWING

THERMONUCLEAR DETONATIONS

by

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SUMMARY

Two cases of chorioretinal burns occurred during Operation Fish Bowl.
These occurred on Johnson Island during a high altitude, night time,
long range, missile-delivered thermonuclear detonation. These two men
were examined within the first 24-28 hours after the injury was
sustained and were followed at less frequent intervals since that
time. The exact size and location of such retinal damage within a
fraction of a millimeter is essential as a basis for prognosis in regard
to the final visual outcome.

VISUAL DECREMENT IN HUMANS FOLLOWING
THERMONUCLEAR DETONATIONS

James F. Culver

INTRODUCTION

For this symposium we have been instructed to consider primarily the effects of
loss of vision on task performance in relation to loss of function in (a) various
parts of the retina, (b) the extent of visual field loss, and (c) the duration of the
blind period. This paper will be limited to the observed effects in humans that have
received retinal damage from actual thermonuclear detonations.

Since the advent of atomic weapons we have been acutely aware of the fact that
retinal damage can occur from such thermal energy at distances far greater than other
known biological effects. The Defense Atomic Support Agency (DASA) has sponsored a
number of field experiments performed by the USAF School of Aerospace Medicine to
define this problem.

The early studies performed in Nevada involving low altitude detonations demonstrated
that chorioretinal burns could be produced in rabbits at distances up to 42.5 miles
(68.4 km)[2,3]. In 1958 we were given the opportunity to carry out experiments involving
detonations at high altitudes, and these experiments confirmed the predictions that
burns could be produced at even greater distances because of the lessened atmospheric
attenuation. Rabbits were exposed during Operation HARDTACK to the radiations from
shot TEAK (a megaton range weapon) detonated at an altitude in excess of 250,000 ft
(76,200 meters). Animals were placed at calculated distances utilizing various
crafts as stations, and under night-time conditions chorioretinal burns were found in
rabbits at slant distances exceeding 300 nautical miles (556 km)[4,6].

Since all the experimental work has involved animals, primarily rabbits or small
primates, it has not been possible to determine adequately the actual visual loss that
has resulted. We have considered, and still have under consideration, the possibility
of utilizing trained small primates, such as the rhesus monkey or perhaps the
chimpanzee to aid in defining this problem. This is a long and tedious process as
well as a very expensive one. It is also not feasible to utilize humans, nor could
we expect very many volunteers except in the rare individual who might have a
malignant lesion necessitating removal of the eye and would volunteer his services.
Because of these difficulties, we have had to rely on experimental studies,
calculations, and close scrutiny of accidental injuries of which we are aware.

ACCIDENTAL CHORIORETINAL BURNS IN MAN

(a) From Solar Eclipse

There exists a large number of clinical reports on eclipse retinitis, and although quantitative aspects of exposure time and energy absorption at the retina are lacking, these cases can provide a large number of clinical reports regarding symptomatology and the rate and degree of recovery of the human retina following such exposure. These patients have reported the rapid development of symptoms, usually from 1 to 4 hours after exposure, and complain of tearing, smarting, blurring, clouding, and dazzling[8]. In severe cases loss of vision was pronounced, but improvement was the rule with time. Most of the clinical studies have been based on examinations performed months after exposure, and the lesions observed in the macular area have varied from small to large diversely shaped single and double holes and in some cases multiple small lesions.

The subjects in these reports experienced a variety of symptoms which included one or more of the following: (1) metamorphopsia, (2) photophobia, (3) disturbances in color vision, (4) scotomata, and (5) persistent afterimages[1].

In the severe cases the scotomata were absolute and resulted in a definite diminution of vision. Most subjects noted some visual recovery several days to several months later, but permanent visual acuity decrement was always found with foveal lesions. These same symptoms and resulting defects can be assumed to occur with similar lesions that could be produced by the thermal energy of a nuclear weapon.

(b) From Low Altitude Nuclear Detonations

Another source of information comes from studies involving humans who have been exposed to such detonations. The first human case reported in the literature was a single case that occurred during the Hiroshima atomic explosion which resulted in a bilateral central scotoma[9]. Six additional cases have occurred during weapons tests when test personnel did not use the recommended eye filters. These were reported by Rose et al. in 1956[10]. In 5 of the cases the lesions occurred near the foveola with resulting paracentral scotomata. The lesions apparently did not involve the entire fovea so that the final visual acuity was 20/25 (6/6) or better. One accident which occurred at a distance of only 2 miles from the detonation produced a large central lesion which included the entire fovea. This resulted in a central scotoma and an immediate drop in visual acuity to 20/200 (6/60). Six weeks later a final recording of 20/70 (6/21) was obtained. All of these cases reported by Rose et al. (1956) resulted from low altitude detonations and occurred at distances of 10 miles (16 km) or less.

(c) From High Altitude Nuclear Detonations

The first two known cases resulting from high altitude thermonuclear detonations occurred during Operation FISHBOWL in October 1962 when chorioretinal burns were accidentally sustained by two test personnel stationed on Johnson Island[5]. These occurred at night from a very high altitude (tens of kilometers) missile delivered device. These men happened to be located at a slant range of over 30 nautical miles (55 km) distance. During this same detonation our animal experiments demonstrated

chorioretinal burns at the most distant station over 100 miles (160 km) away. The previously reported cases that occurred during low altitude weapons tests involved only one eye in 4 of the 6 cases. The two men stationed on Johnson Island received bilateral chorioretinal burns, and, as in the earlier 1956 accidents, neither the Air Force sergeant nor the Navy petty officer had his protective goggles in proper position at time zero. Physicians were able to observe these men at Johnson Island and at Hickam Air Force Base within the first 24 to 48 hours, and close observations were continued for more than 6 months. Initial hospitalization was at Tripler General Hospital, and later they were transferred to the USAF School of Aerospace Medicine for continued close follow-up care and observation.

Immediate visual disturbances were reported by both subjects consisting of a transient blinding 'white sheet of light' which cleared rather rapidly leaving a central glowing positive scotoma followed by a small central negative scotoma. Neither could relate adequate information regarding the exact degree of immediate incapacitation experienced since there was no occasion for instruments, maps, or printed material to be immediately utilized. The Air Force sergeant first realized something was wrong when he viewed the control tower lights and noticed they would appear and disappear as he moved his eyes. He was never blinded to the extent that he could not get about, and he reported to the dispensary within approximately 30 minutes. The Navy petty officer did not report for medical care until the following day. Shortly after the initial symptoms, he prepared for bed, and upon looking into the mirror he described what appeared to be a glowing afterimage about 6 in. (15 cm) in size. He slept for approximately 4 hours, and upon awakening was aware of a definite blind spot in the center of his vision. He boarded a P2V aircraft for routine duty but noted that on looking directly at the tip tank at the end of the wing it would disappear entirely.

Ophthalmoscopic examinations revealed generally similar lesions in both patients. The chorioretinal lesions in the Air Force sergeant appeared as a circular white area approximately 0.35 mm in diameter with a circumscribed area of erythema surrounding the white spot and extending out to a diameter of approximately 0.85 mm. The remainder of the fundus appeared normal. The lesions in the eyes of the petty officer appeared similar, with the white central areas being slightly larger, measuring about 0.50 mm in diameter. In Figure 1 the grid squares in the photograph correspond to approximately 0.34×0.34 mm in size. On the initial central field examinations both patients exhibited absolute scotomata in each eye. A circular scotoma of approximately 1.5 degrees with a tail-like superior extension was found bilaterally in the Air Force sergeant. A slightly larger central scotoma of about 2.5 degrees was demonstrated in the petty officer, but no tail-like extension could be defined. Figures 2 and 3 portray visual field examinations which graphically demonstrate the course of the scotomata in the two patients over a 6-month period. The tail-like extension of the scotoma found in the Air Force sergeant disappeared within the first 2 weeks, and the central scotoma became slightly smaller after a period of 6 months. The majority of the examiners agreed that the scotoma in effect was slightly paracentral. The scotoma in the case of the petty officer was absolute and central, and increased slightly during the ensuing 6 months.

The visual acuity recording for each patient depended on how the patient was asked to fixate: direct central (looking directly at the letter) and off central or eccentric acuities were recorded. By direct viewing, the Air Force sergeant could

barely discern a 20/400 (6/120) target at the 24-hour postexposure examination. His
eccentric acuity was recorded initially as 20/40 (6/12) in each eye, decreasing to
20/100 (6/30) at 24 hours, and then improved to 20/60 (6/18) at about 48 hours. The
petty officer on initial examination at 48 hours postexposure demonstrated direct
central acuity of less than 20/400 (6/120) and eccentric acuity of 20/60 (6/18) in
each eye.

During the following 6 months while at the USAF School of Aerospace Medicine,
numerous parameters were considered: (1) observation of the subjects in their
assigned job positions at Brooks Air Force Base; (2) history of subjective visual
complaints; (3) acuity measurements at near and distance; (4) reading ability;
(5) ocular motility evaluation; (6) color vision testing; (7) depth perception
testing; (8) accommodation measurements; (9) biomicroscopy and funduscopy; (10) Haidinger
brush perception using the Cupper's Koordinator; (11) intraocular tension; and
(12) visual field charting.

At the end of this 6-month period the Air Force sergeant's visual acuity at near
and distance was 20/25 (6/7) in each eye, and his reading ability was good. On holding
his eyes stationary, he was aware of a very small central negative scotoma which
blanked out individual letters. The most difficult of the stereopsis tests, which
utilizes the visual testing apparatus (VTA), revealed a measurable defect; however, he
passed other methods of depth perception testing, such as the Howard Dolman test. The
bilateral absolute scotomata measured approximately 1 degree at the end of 6 months,
and all other measurements were within normal limits. He performed unusually well in
his job and had minimal subjective complaints.

The best vision recorded for the US Navy petty officer after 6 months was 20/60
(6/18) bilaterally, and he was not as effective in his assigned duties. Visuscopic
examination revealed his fixation to be unsteady, whereas the sergeant's fixation was
steady. Because of his subnormal visual acuity it was necessary that printed material
be held quite close to the face for reading. At a distance of 30 cm he could read
newsprint although he was definitely aware of a small central scotoma (a normal subject
can read ordinary newsprint at a distance of about 100 cm). The central scotoma by
this time had increased slightly in size from the initial examination, and on
ophthalmoscopic examination small cystoid degenerative changes could be noted
surrounding the central lesion. It is logical to assume that these degenerative
changes could account for the slight increase in the size of the scotoma, as noted in
Figure 3. The depth perception studies were similar to those of the Air Force
sergeant, and there were no other abnormal ocular findings.

Although these incidents were most unfortunate, they did provide an unusual
opportunity for careful and detailed study of centrally located chorioretinal burns and
well illustrate that the exact size and position of such lesions are most significant.
From the findings it may be conjectured that the Air Force sergeant was looking
almost directly at the detonation when it occurred (or at a specular reflection of the
detonation), then looked down quickly (the eye being in motion at the onset) and
blinked. This could possibly explain the appearance of the paracentral scotoma with
the early tail-like extension. Insufficient energy apparently was deposited in the
retinal area corresponding to this tail-like extension to cause permanent damage, for
within a few days this tail-like defect could no longer be detected on visual field
examination. It appears that most of the energy received was deposited slightly below

the foveola; therefore, the entire fovea was not destroyed, and a paracentral scotoma bilaterally of approximately 1 degree resulted.

The fovea was apparently destroyed in the case of the petty officer, and there is no doubt that more energy was absorbed. This could be the result of either a longer exposure time or observation during a different segment of the time history of the fireball and perhaps was also due to some difference in pigmentation of the fundus.

A study of these cases confirms what we all know — that chorioretinal burns do not ordinarily result in complete blindness, and incapacitation depends upon the exact location and size of the lesion. Certainly, if either of these chorioretinal burns had occurred in the periphery, they would hardly have been noticed subjectively. Even a lesion as large as 5 mm in the periphery would probably cause no functional distress. If possibly the optic disc, which measures approximately 1.5 mm, or the papillomacular bundle, measuring approximately 3.5 mm, is involved, then a definite defect would be noticed. We are aware that the loss of visual function is related to the distribution of the nerve fibers, and vision may be lost to a greater extent than expected from the lesion size. Figure 4 illustrates such defects that we could expect to result from a 0.7 mm lesion at various locations in the retina.

The fovea measures approximately 0.44 mm in diameter, and when the fireball is focused upon it, the most serious damage to vision occurs. The macula extends out to a diameter of 1.7 mm, and less critical but major functional impairment is noted when it is primarily affected and the foveola is spared for the most part.

The lesions in the Air Force sergeant did not involve the entire fovea; therefore, his visual acuity returned to 20/25 (6/7) bilaterally so that he has been able to return to his duties. The lesions in the petty officer were only slightly larger but graphically portray the more important consideration of position of the lesion. In this case the fireball was imaged on the retina a fraction of a millimeter higher than in the case of the sergeant, and the resulting lesion involved the entire fovea. As a result, his final visual acuity was 20/60 (6/18) bilaterally. He has now been discharged from the Navy with a disability rating at 30%; however, he is by no means a visual cripple and can perform many useful occupations.

I would like to present one further point for your consideration for which I have no adequate explanation. Probability studies indicate that the chances of receiving a macular burn are 0.01 assuming a search field of approximately 40 degrees and only 0.001 considering a search area of 180 degrees[11]. Due to the markedly high altitude of this detonation, the intense thermal energy producing this retinal damage occurred in less than 70 milliseconds and yet both men sustained macular burns. Such an occurrence is most difficult to explain and may indicate that the probability for a macular burn is higher than predicted if we assume these were the only two men that were not properly wearing their protective goggles. It is also quite possible that others did not properly utilize their protective equipment and may have sustained peripheral burns of which they are unaware.

With the increasing use of lasers and masers in the military services and private industry, we are being confronted with similar problems[7]. We as physicians recognize such dangers and insist that the precautionary measures necessary to prevent such an accident be utilized. If such accidents unfortunately occur, they should be well documented and studied.

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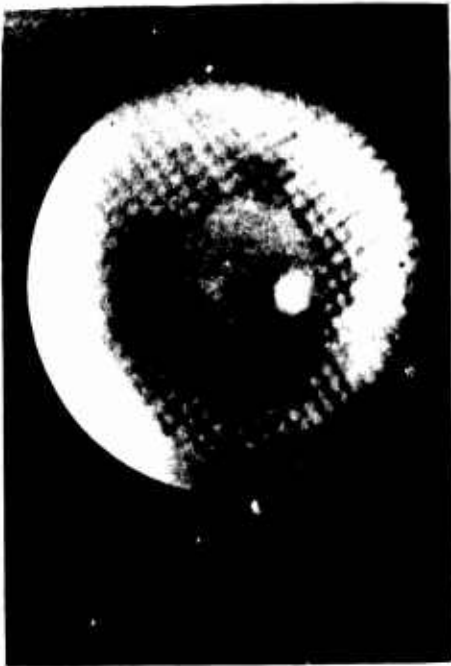
Left eye

Left eye

First patient
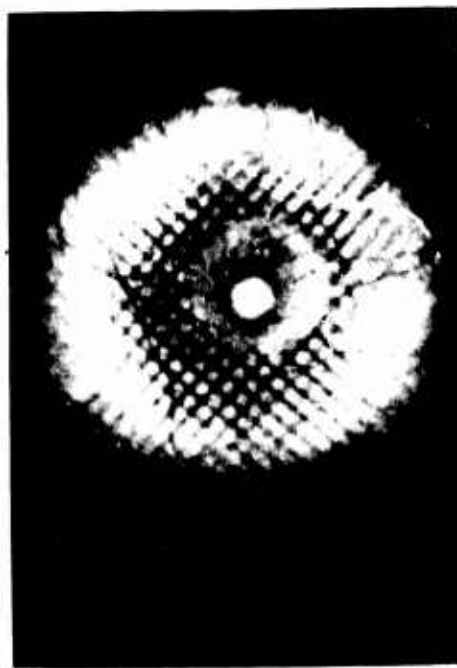
Second patient

Right eye

Right eye
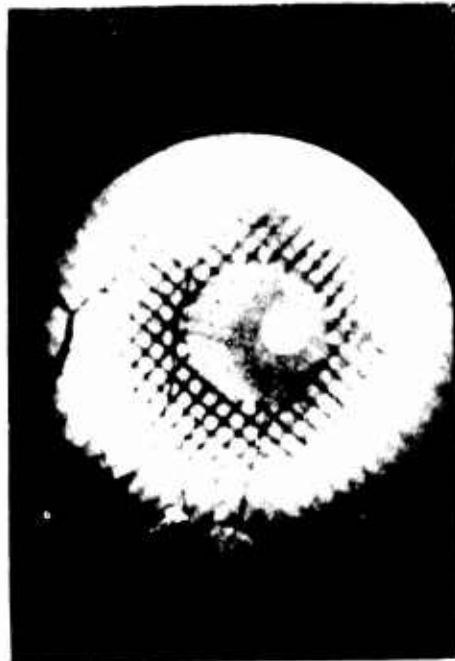
Fig.1   Fundus photographs (Culver *et al*: Aerospace Medicine, 35, 1964)

48 HOURS POST EXPOSURE

I WEEK POST EXPOSURE

3 WEEKS POST EXPOSURE

3 MONTHS POST EXPOSURE

4 MONTHS POST EXPOSURE

6 MONTHS POST EXPOSURE
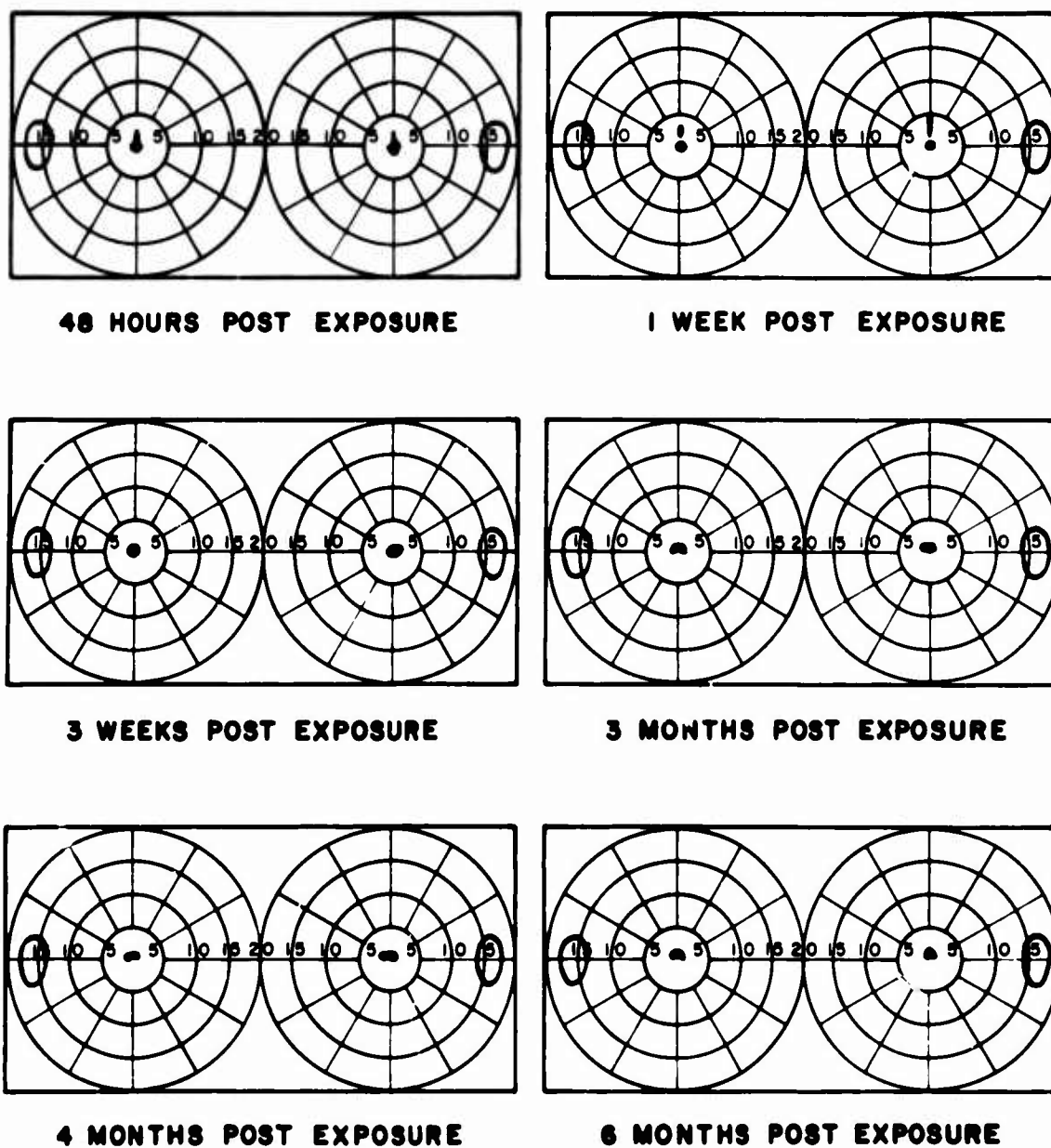
Fig. 2　Tangent screen examinations (Culver *et al*: Aerospace Medicine, 35, 1964)
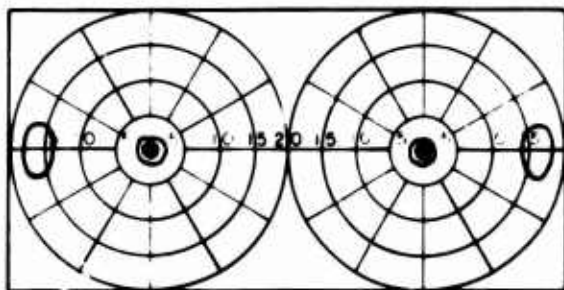
48 HOURS POST EXPOSURE
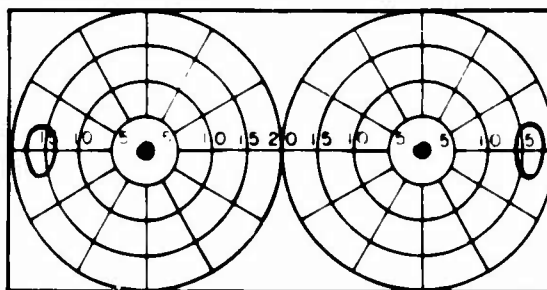
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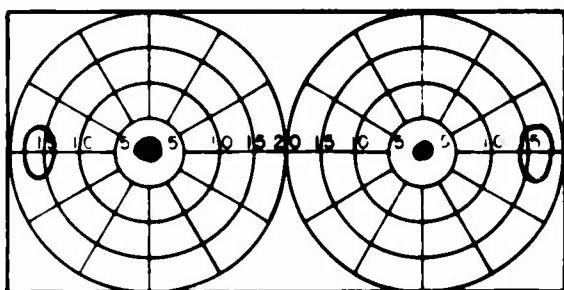
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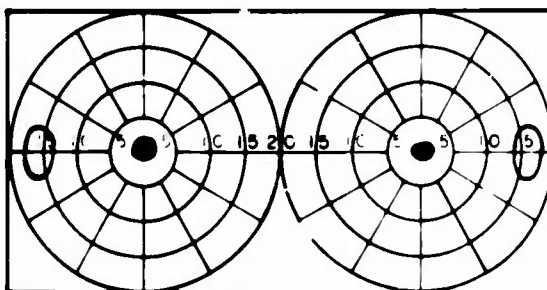
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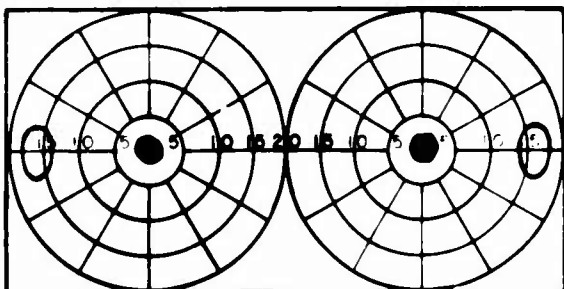
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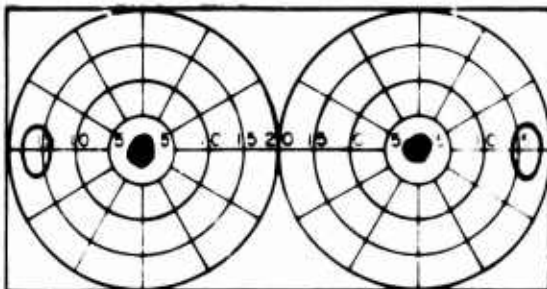
6 MONTHS POST EXPOSURE

Fig. 3   Tangent screen examinations (Culver *et al*: Aerospace Medicine, 35, 1964)

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Fig. 4   Tangent screen examination (Culver et al: Aerospace Medicine, 35, 1964)

WHAT IS THE FUNCTIONAL DAMAGE
THRESHOLD FOR RETINAL BURN?

by

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SUMMARY

The simplest method of determining the threshold irradiation dose for a retinal burn is to examine the fundus by ophthalmoscopy. There is no guarantee, however, that this threshold coincides with the functional threshold.

Geeraets *et al* have shown a reduction of enzyme activity in the retina below the threshold for ophthalmoscopic or histologically detectable lesions. Interpretation of their data in terms of a quantitative model of enzyme destruction enables us to determine the sensitivity to temperature rise of retinal enzymes and thus to get a closer approach to the problem of functional damage.

WHAT IS THE FUNCTIONAL DAMAGE
THRESHOLD FOR RETINAL BURN?

J.J.Vos, W.T.Ham Jr and W.J.Geeraets

1. INTRODUCTION

Loss of vision from high-intensity light may be due, either to flash blindness or to retinal burn. The two are essentially different. The first effect is due to stimulation - true, to an excessive degree - of the sensory system, whereas the second effect is due to stimulation - by heat, or worse, by explosive forces - of the receptive and nervous tissues. Flash blindness may be investigated experimentally in man as long as the safety level for retinal burn is not exceeded. Retinal burns, however, can only be studied by indirect methods. Only careful evaluation of experimental data on animals in terms of theoretical models may lead to damage threshold data in which we can have confidence. An attempt at such an evaluation of the experimental data has been made.

2. OPHTHALMOSCOPIC CRITERIA

The oldest, and simplest method of evaluation is to examine the fundus by ophthalmoscopy. This method was applied in the early investigations of Ham and co-workers (1957, 1958). As "just visible" they considered an ophthalmoscopically observable lesion two to three minutes after the exposure. With this criterion they obtained reproducible results, but of course this damage threshold is somewhat arbitrary, because similar functional effects may be produced at much lower levels of irradiation.

In an attempt to elucidate the relation between the ophthalmoscopic and the functional damage threshold, Vos (1962) computed the retinal temperatures which must have been attained during the exposure in Ham *et al's* experiments. It turned out that the threshold data did not coincide with levels computed on the assumption that one certain critical temperature should not be exceeded (Fig.1).

Moreover, the dose to produce small size lesions appeared to have been so high that retinal temperatures above 100°C can hardly have been avoided. It cannot be excluded, therefore, that the damage in these first experiments at the Medical College of Virginia may have been due to micro steam explosions, rather than to direct thermal effects Though only a rough quantitative evaluation could be made, it seemed to corroborate this view. It therefore was concluded that the functional damage threshold might be distinctly lower than that found ophthalmoscopically.

The history of burn research has confirmed this surmise. Improvement of the ophthalmoscopic technique (use of red free light, placing of "landmarks" in the retinal environment) and studies of the reduction in enzyme activity have reduced the lesion threshold by a factor of three (Geeraets *et al*, 1963). This is also demonstrated by the histological appearance of the minimal lesions in course of time (Fig. 2).

Though it is progress, to have a better value for the threshold dose, it makes one curious whether new techniques might reveal damage at even lower doses of irradiation. In other words: have we now reached the final damage value, or is there reason to assume that we are still above the level of functional damage?

3. HISTOCHEMICAL CRITERIA

Study of the histochemical changes after exposure has revealed interesting features. Geeraets and co-workers (1963, 1965) have extensively described how one can follow the heat flow, as it were, by studying changes in staining of enzyme rich layers of the retina. Enzymes are known to be sensitive to small changes in temperature and therefore they serve as a kind of built in thermo-indicators. The staining pictures show, for instance, that with increasing dose, the "heat front" advances more and more into the retinal layers (Fig. 3).

It is interesting, moreover to notice the differences between the staining picture for the mild 175 μsec lesion (Figure 3, bottom), and for an equally mild 30 msec lesion (Fig. 4). Apparently the heat has diffused even to the ganglion cell layer in the latter case.

What can we conclude from these experiments?

In the first place we have in them a check on the reliability of temperature computations. In the second place the alteration of enzyme activity seems to be closer to the functional damage concept than the ophthalmoscopic change in the fundus appearance. The latter seems to be related to oedoematous reactions of the living organism to excessive irradiation — if not explosions — and seems not to be entirely associated with retinal burns.

In order to have the full profit of this new understanding we have, again, to be more quantitative in our evaluation.

4. RATE PROCESS MODEL

As a first approach we can simply calculate the temperature course for each retinal level of interest in the staining experiments, and we then find that the experimental data fit quite well with one critical temperature level on the spot (Fig. 5). That temperature level is about 50°C, under the assumption that all incident energy is absorbed in the pigment epithelium. But if this is not so — and absorption data of Geeraets *et al* (1960) indicate that some 50% absorption is a better choice — this maximum admissable temperature for undisturbed DPN diaphorase activity would only be some 44°C.

But of course this description is not accurate as it does not include the time factor. Chemical reactions are rate processes, and damage to the enzyme activity is not of an "all or none" type. Intermediate damage levels occur as well, as demonstrated by Geeraets *et al* (1963). In particular the DPN diaphorase staining pictures of the ellipsoid layers show that the borders of the "thermal" image may be unsharp after prolonged - that is: not shorter than 30 msec - exposure, but rather sharp after short exposures in the order of 200 μsec (Fig.6).

Now actually the temperature - time history in these two situations is only slightly different. The distance of 40 micron to travel between pigment epithelium and ellipsoids in the rabbit eye, is thermally so long that the diffusion has markedly smoothed the sharp-cut features (Fig.7).

That such a small difference in temperature course given significantly different staining pictures can leave only little freedom in choice of the reaction rate parameters. Let us, tentatively, make two different assumptions.

(a) Suppose the rate k of the enzyme inactivation process is only slowly increasing with the temperature rise T - say $k \sim T$. This would mean that the area under the T versus t curve is a direct measure for the total damage $\int k\,dt$. But, as explained, these areas hardly differ for 30 msec and a 175 μsec exposures: the temperature versus time curves almost exactly coincide over a great part of their after-exposure tails and only show small differences in their first parts. As a result we should expect a blurred image border in either situation. But that is contrary to the experimental evidence.

(b) Suppose the rate k is strongly dependent on the temperature rise T . To put it extremely k = 0 for $T < T_{cr}$, and $k = \infty$ for $T > T_{cr}$. In that case the damage occurs on an all or none basis of course. This means that no intermediate staining can exist, that both the 175 μsec and 30 msec staining image should be sharp. Which, again, is contrary to experimental evidence.

With these two examples we have more or less quantitatively illustrated our point that there is restricted room only for a well fitting choice of the rate characteristics of the enzyme inactivation reaction.

Now, assuming that the inactivation reaction is a simple first order irreversible chemical reaction, we can expect a dependency of k on T according

$$k = k_0 e^{-P/T} \quad \text{(Henriques, 1947)}$$

which formula essentially reflects a Boltzmann chance distribution. P is a parameter which determines the steepness of the k versus T curve. Usually this steepness is indicated by

$$Q_{10} = \frac{k_{T+10}}{k_T} = \frac{e^{-P/T+10}}{e^{-P/T}} \simeq e^{10P/T^2} \simeq e^{10^{-4}P}$$

at body temperature $(T = 273^o + 37^o = 310^o)$.

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Ordinary single-bond anorganic reactions have a Q_{10} = 1 to 3 , corresponding to $P = 10^4$; multiple-bond reactions as occurring in proteins can be expected to have a much higher Q_{10} of the order of thousands. $P = 10^5$, for instance, corresponds to Q_{10} = 22,000 . By varying P we can scan all kinds of intermediate k versus T courses and try out whether they give a satisfactory description of the border sharpness. We can quantify this approach in the following way. Suppose $n(t)$ represents the fraction of the original amount of enzyme still active at time t . Then

$$\int_0^t k(\tau) \, n(\tau) \, d\tau$$

represents the fraction of the enzyme inactivated by the thermal reaction until time t . As the fraction altered is equal to 1 - the fraction still active, we have

$$\int_0^t k(\tau) \, n(\tau) \, d\tau \;=\; 1 - n(t) \quad .$$

This integral equation can be solved if we know the k versus T relation (essentially Q_{10} , therefore) and the T versus τ relation which can be computed at any place of the retina wanted. The final answer we are interested in is $n(\infty)$, the residual fraction of active enzyme left after the temperature has retained its normal level. Computed in this way for places near the image border it should give, for the appropriate choice of Q_{10} , a border which corresponds to that experimentally found.

The results obtained by trial (in Q_{10}) and error (in getting a fit) (Fig.8) show that $Q_{10} \simeq 1000$ gives a best fitting description of the chemical rate process. It should be noted that this value is derived under the assumption that all energy is absorbed. A 50% choice, as mentioned, would lead to 2 times higher Q_{10} values. But that is only a question of absolute calibration and does not affect the model essentially.

8. CONCLUSIONS

The damage threshold for retinal burns seems to be better defined now then eight years ago. The rather arbitrary "ophthalmoscopical" threshold could be replaced by the lower "histochemical" threshold which can be better understood in terms of a mathematical model.

This is of importance when we want to extrapolate our knowledge of danger criteria to less well investigated situations of excessive light exposure. Critical doses for focused laser beams, as specified in current safety prescriptions (Ministry of Aviation, 1964), largely depend on an interpretation of experimental data on large irradiation fields. Similarly evaluation of retinal damage after looking into a nuclear flash, or in situations of sun blindness has to rely upon interpretation of indirect experimental evidence, since direct experiments on human eyes are excluded. In all these situations, advance evaluation is only possible

(a) when we know we can rely on the temperature computations. This is assured to a high degree by the correspondence between the computation data and the histochemical results,

(b) when we understand which is the critical point in determining whether there is a functional retinal burn or not. The combined results of histochemical techniques and mathematical analysis seem to indicate that we have come more near to the evaluation of functional damage.

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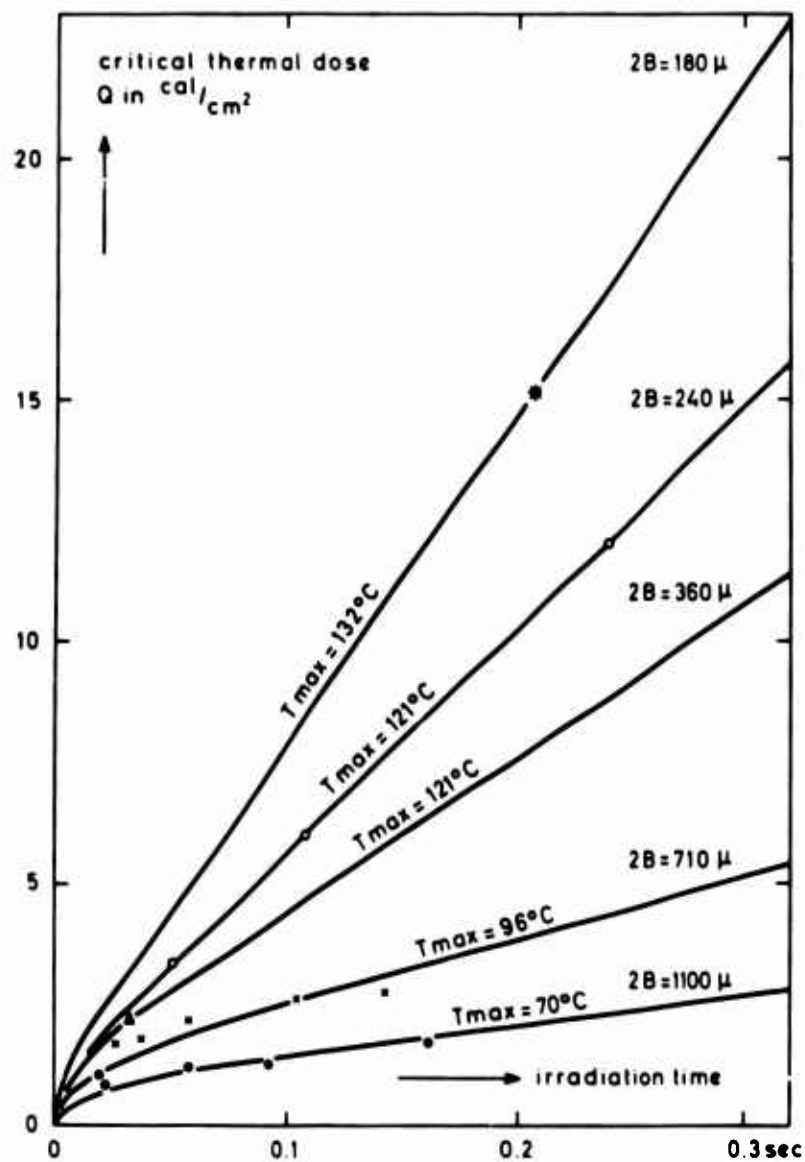
Fig.1 The critical thermal dose upon the retina as a function of exposure time for
various sizes of the irradiated area, according to Ham *et al* (1958).
Lines of constant maximum term temperature in the image center are drawn
according to best visual fit (Vos, 1962). The maximum temperatures indicated,
computed on the basis of 50% absorption in the pigment epithelium,
appear to depend on the image size
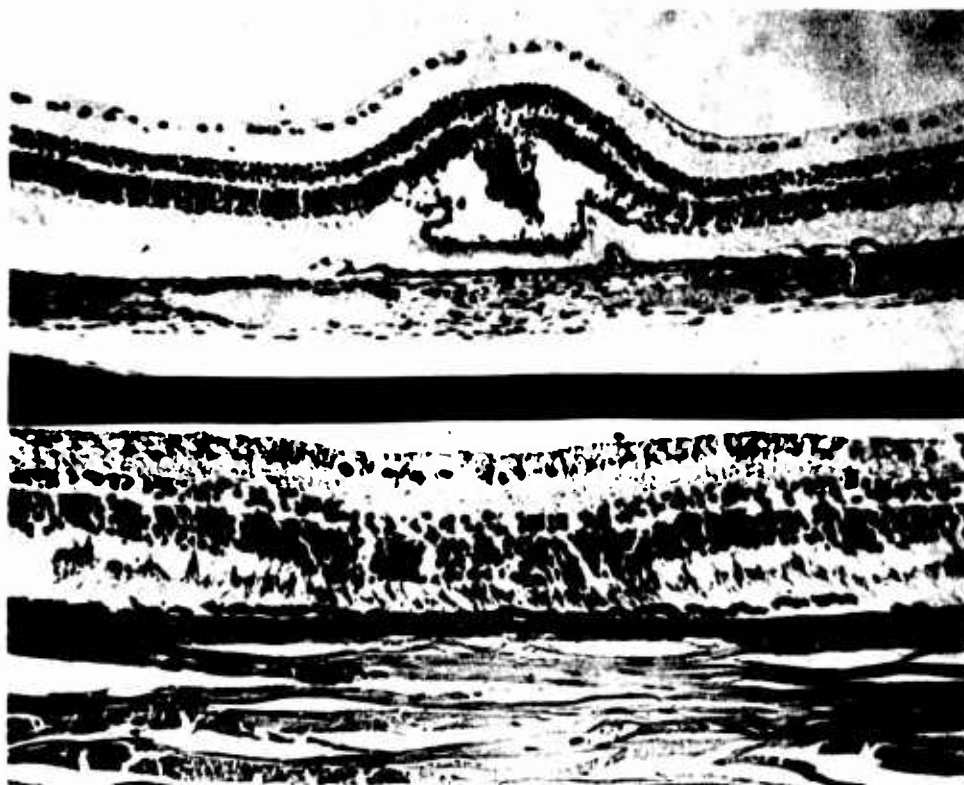
Fig. 2   Maximal thermal lesion (paraffin section. hematoxylin-eosin) according to the
original classification (top) and according to more recent
classification (bottom)

Fig.3 Histochemical appearance of retina sections after irradiation for 175 μsec.
Stained for DPN diaphorase activity. After a minimum lesion dose the
staining is completely intact in both the ellipsoid and the ganglion cell
layer (top); after a mild lesion dose the heat has affected the enzyme,
in the ellipsoid layer (bottom). (Geeraets *et al* (1965)

Fig.4   Histochemical appearance of a retina section after irradiation for 30 msec
to a mild lesion.   Stained for DPN diaphorase activity.   The heat has now
affected even the ganglion cell layer.   (Geeraets *et al* 1963)

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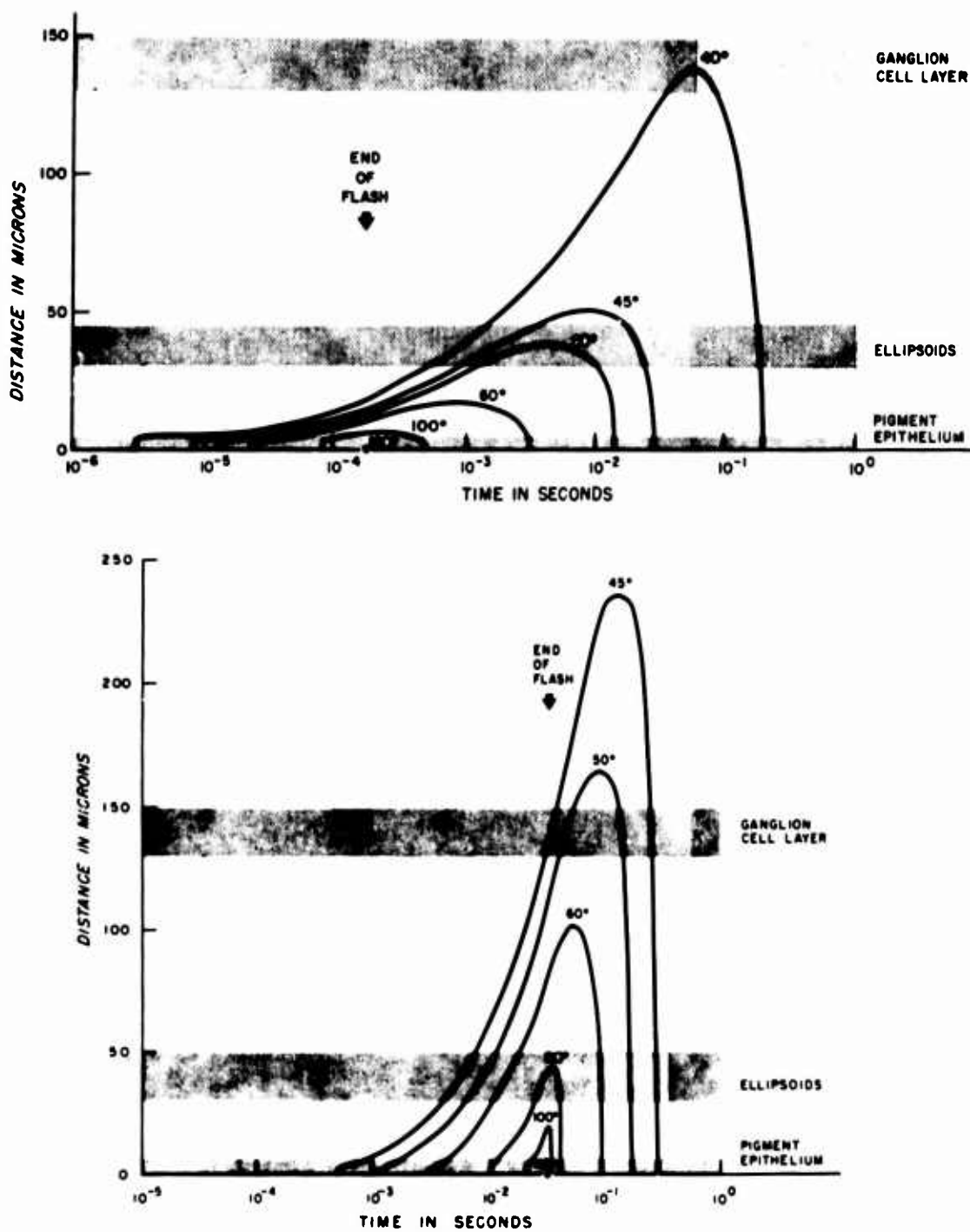
Fig. 5 Calculated temperature versus time distribution over the retina after
absorption of a large field light flash in the pigment epithelium.
The upper picture corresponds to the stimulus situation of Figure 3,
bottom (175 μsec), the lower picture to that of Figure 4 (30 msec)

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Fig.6 Minimal lesions after short exposure time (175 μsec left side) give considerably sharper edged staining pictures in the mitochondria layer than those after longer exposures (30 msec, right side)
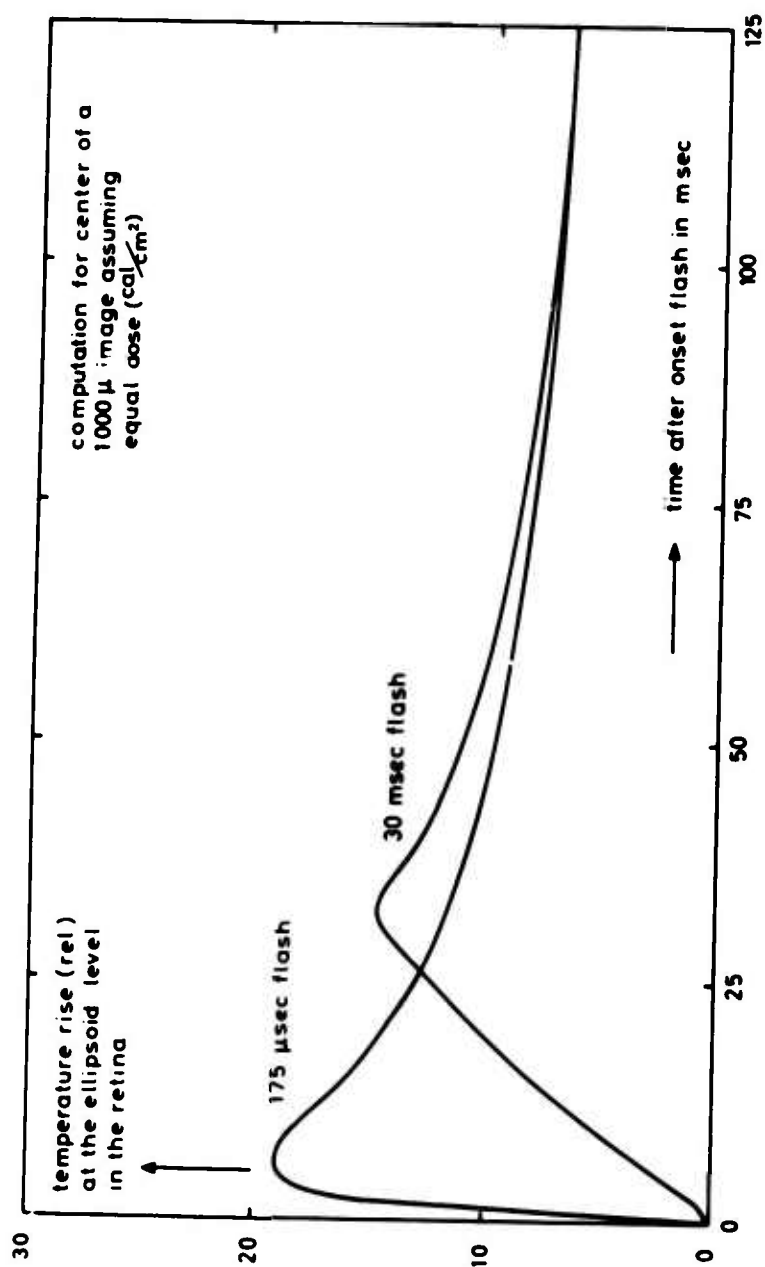
Fig.7 Temperature-time course in the ellipsoid layer by irradiation during 175 μsec and 30 msec respectively
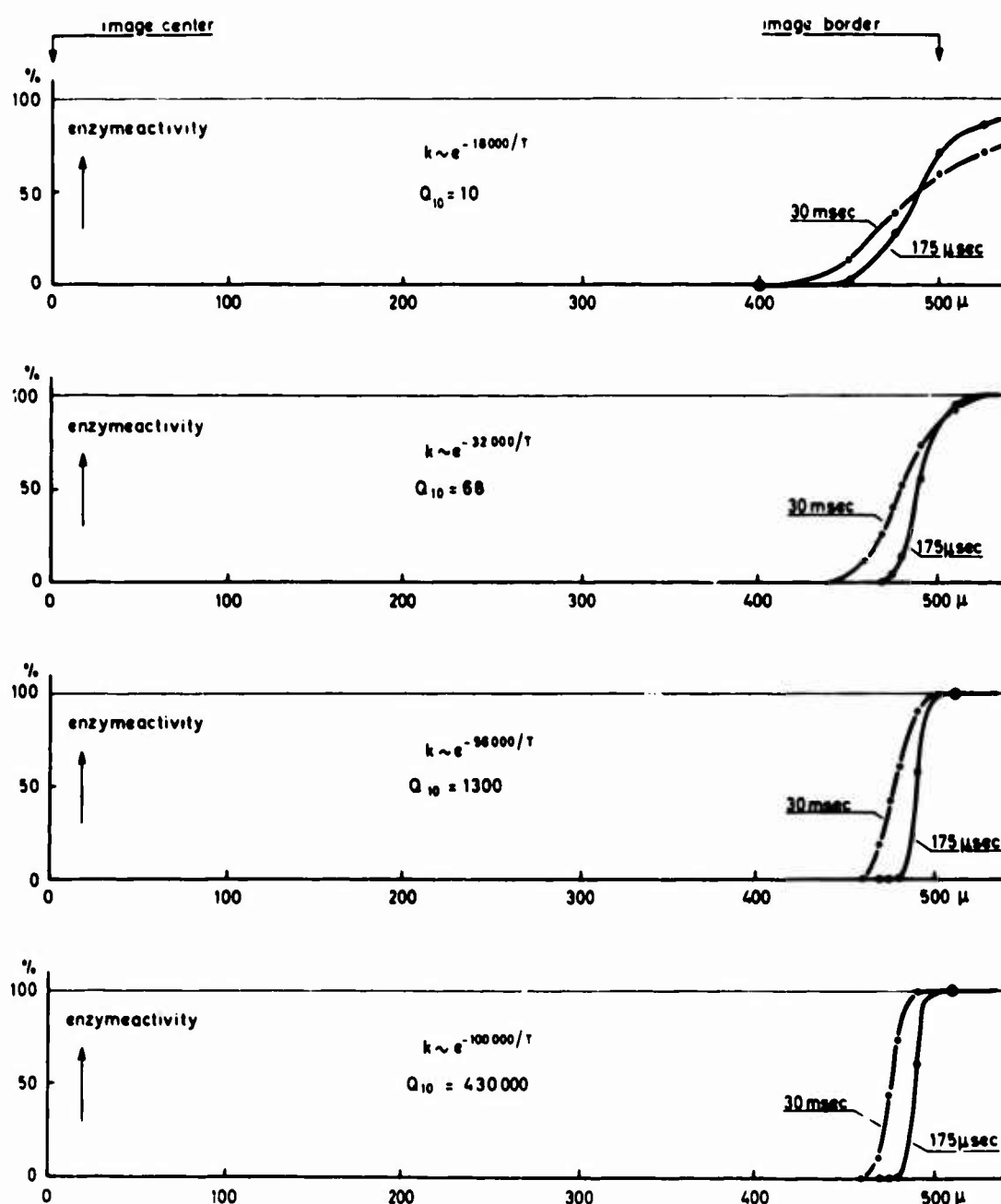
Fig.8   Computed sharpness of the staining image border after 175 μsec and 30 msec
exposure for various choices of Q_{10}.   A choice of Q_{10} in the
neighbourhood of 1000 seems to give the best differentiation between
the two staining pictures, according to the experimental finding of
Figure 6

VISUAL AND RETINAL EFFECTS OF EXPOSURE TO HIGH INTENSITY LIGHT SOURCES

by

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SUMMARY

This paper presents a quantitative analysis of: (1) transient loss of
visual function (flash blindness), and (2) irreversible thermal injury of
the retina. The measure selected for flash blindness has been the
bleaching of a significant fraction of the visual pigments, and the
criterion for retinal burn has been the minimal lesion seen ophthalmo-
scopically. It was then possible to determine, for each effect, the
threshold retinal radiant exposure as a function of wavelength.

The computations showed that for some wavelengths, particularly those
emitted by the usual laser sources, the retinal burn threshold may be
greatly exceeded before marked "visual" impairment is produced.

VISUAL AND RETINAL EFFECTS OF EXPOSURE TO
HIGH INTENSITY LIGHT SOURCES

Milton M. Zaret and Gerard M. Grosof

Problems relating to changes in the visual system following exposure to high-intensity lights have stimulated much investigative work recently[1-8]. This can be attributed in part to the military significance of such problems, and in part to the advent of new techniques for the study of visual processes.

As regards the latter, many experiments concerned with the analysis of electro-retinal activity or visual photochemistry require intense light stimuli to bleach (isomerize) a significant fraction of the visual pigments[2, 4, 5, 8]. With respect to the military interests, on the other hand, the visual effect is often an undesirable by-product of the environment. Nevertheless, it is obviously important to know the degree of functional impairment resulting from exposure to the atomic fireball, the emission of a laser source, and the like. Furthermore, since irreversible tissue destruction may result from such exposure, much effort is being expended in determining the so-called "burn threshold", and in the development of appropriate protective devices. Although here we are concerned primarily with the needs of the military, we shall of necessity refer to the experimental findings of the vision physiologist.

In essence, we will consider two distinct but related effects of high intensity exposure: (1) the *transient* loss of visual function known as flash blindness, and (2) the *irreversible* ocular injury produced by photocoagulation. To demonstrate how these effects are related quantitatively is the object of this communique. Specifically, we will approach the analysis by examining the intensity levels used in studies of flash blindness. And the question we will attempt to answer is: Given a desired *visual* effect (i.e. degree of flash blindness),. is the injury threshold exceeded?

Now this is not the conventional way of looking at the relation between flash blindness and retinal burn. It is usually assumed that flash blindness precedes irreversible injury on the scale of intensities. For example, in an excellent review article published recently[7], it was stated that "injury t the eye may not be as serious a problem as the transient reduction in sensitivity which follows illumination at high levels". Since few will deny that a retinal bu is at least as serious as flash blindness, this comment clearly implies that flash blindness occurs at intensity levels *below* those which cause ocular injury. But this is not the case for all wave-lengths in the electromagnetic spectrum – and, as we will show, is a particularly dangerous generalization when the common laser emissions are considered. Indeed, many experiments utilizing "white" light sources for the study of flash blindness involve exposures that may be harmful to ocular tissue.

Presenting the inter-relations between flash blindness and thermal injury creates a unique problem, for neither has been adequately defined. In considering flash blindness, we should ask: Flash blinded to what extent? What recovery time is considered insignificantly short? Is it the scotopic (rod) or photopic (cone) system that is of concern? And a return to what sensitivity or resolution is evidence of "recovery"? Analogous questions arise in regard to the threshold of irreversible damage: Is it the retinal lesion seen ophthalmoscopically? Or the changes viewed with the electron microscope? Or is it the dramatic alterations in the vascular system demonstrated by Dr Dollery[9] with fluorescein retinograms? Perhaps a decision on these matters is forthcoming. For the present, however, it will suffice to illustrate an approach to the problem by adopting somewhat arbitrary criteria for flash blindness and the burn threshold.

As regards thresholds for thermal damage, we will make use of the excellent data provided by Dr Ham and his associates[10,11] for the ophthalmoscopic signs of retinal injury. Flash blindness, on the other hand, will be equated with the bleaching of a significant fraction of the visual pigments. This oversimplification is necessary if we are to avoid a description of all the parameters which define the visual effect of a light flash.

One may, of course, question the rationale for considering an effect upon the visual pigments as a criterion for flash blindness, since measurable bleaching occurs only at intensities well above ordinary luminance levels.. Figure 1, modified from a paper by Weale[12], illustrates this point. The absolute thresholds of the rods and cones (for white light) are indicated at -4.0 and -1.0 log td.-sec, respectively. Note that the retinal illuminance has to be increased about 9 logarithmic units before more than 1% of the visual pigment is bleached. Even the rod saturation level, the intensity at which Aguilar and Stiles[13] found that the rods are responding maximally and are unable to detect further increases in brightness, occurs before a significant amount of visual pigment is bleached.

The visual pigment concentration begins to be affected only when the intensity reaches about 100,000 td.-sec and decreases rapidly with further increase in intensity. The curve represents the fraction of pigment bleached calculated from the well-known expression[14].

$$\frac{c_b}{c_0} = 1 - e^{-\alpha\gamma It}$$

where c_b is the concentration bleached b at exposure It
c_0, the original pigment concentration
It, the retinal irradiance in troland-seconds
and $\alpha\gamma$ is the photosensitivity expressed in $(td.-sec)^{-1}$. In the case of the human visual pigments the value of $\alpha\gamma$ is approximately 10^{-7} $(td.-sec)^{-1}$ (cf. Rushton[15] and Weale[16]).

Also indicated on the graph is the retinal radiant exposures which produce threshold burns for several exposure durations. Noteworthy is the fact that for *white* light, complete bleaching can be achieved before ophthalmoscopic signs of retinal coagulation occur. However, for brief exposures (i.e. 30 nanosec.), a factor of only 3 separates these effects.

As to why we have selected flash-blinding criteria that require such high intensities, some justification can be offered from a consideration of the data of dark adaptometry. In general, flash blindness is of no consequence unless visual sensitivity is impaired for an appreciable time interval following exposure; and the dark adaptation curve is conventionally used to indicate the level of sensitivity as a function of time. The continuous curve of Figure 2 shows the course of peripheral dark adaptation following an exposure that bleaches approximately 90% of the visual pigments within the test region. As is well known, the extra-foveal dark-adaptation curve of the normal eye is bipartite, the early and late parts representing the adaptation of the cone and rod mechanisms respectively. In Figure 2 we see that the cone branch follows an extended course with the minimum threshold level occurring after about ten minutes in darkness. Rod thresholds, which are at first masked by the greater sensitivity of the cones, appear almost fifteen minutes after the cessation of the flash, and continue to fall for the next twenty minutes until maximum sensitivity (absolute threshold) is reached.

It is clear that the adapting flash used in this experiment has flash-blinded the eye, and recovery of vision is a prolonged process. If, however, the adapting exposure is sufficient only to saturate completely the rod system (see Fig. 1), dark adaptation proceeds in the manner shown by the dashed-line curve of Figure 2. The cone branch is practically non-existent, indicating that cone sensitivity has hardly been altered. And even the rods adapt quickly to their absolute threshold level. It is probably the case, therefore, that to produce a significant flash-blinding effect (particularly as regards the cone mechanism) requires a significant pigment bleach.

Figure 3 gives essentially a closer look at the high intensity end of Figure 1. But here the fraction of cone pigment bleached is plotted as a function of log retinal radiant exposure in cal/cm^2. The different curves represent three sources, each of which emits a characteristic wavelength distribution. The reason the laser curves are displaced to higher intensities is due to the lower absorptive properties of the visual pigments for the long wavelength emission of these devices. For example, a neodymium curve (not shown) would be displaced approximately 7 log units to the right of the ruby function. Naturally, the number of troland-seconds to produce a given bleach is constant, as shown on the right-hand scale of ordinates.

The significant feature of this graph is that if one can merely specify the intensity of a flash, and its wavelength, we can compute the fraction of pigment bleached and where one is with respect to the burn threshold. The latter, indicated by the vertical dashed lines, varies as a function of exposure time due to the failure of the reciprocity law for thermal injury. For example, with an exposure duration of 0.1 sec. (approximately the blink-reflex time), a greater radiant exposure is required for producing a retinal burn than with a 1 msec. exposure (the discharge time of the ordinary pulsed ruby laser). Although not shown in the diagram, only -1.7 log cal/cm^2 is needed for thermal injury when the exposure duration is reduced to Q-switched times of 30 nanosec. Thus, both pulsed and Q-switched ruby lasers will coagulate the retina before our "visual" criterion of 90% pigment bleach is attained. However, the retinal radiant exposures required to produce a 90% bleach with the He-Ne laser and "white" light give this effect before an ophthalmoscopically visible lesion is formed.

The curves of Figure 3 show the effect of varying the retinal radiant exposure on the photopigments for a few selected light sources. Alternatively, one can specify a criterion bleaching level, and then determine the retinal exposure required, at any

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wavelength, to produce this effect. The results are shown in Figure 4 where the retinal radiant exposure in log cal/cm^2 refers now to that needed to (A) bleach 90% of the cone pigments*, (B) bleach 90% of the rhodopsin content of the rods, or (C) saturate the rod mechanism. In this graph, the thresholds for thermal injury are indicated for two exposure durations by horizontal dashed lines.

Now one of the dangers mentioned earlier was that in attempting to flash-blind, the burn threshold may be exceeded. With white light, it was shown that flash blindness can be achieved with a retinal exposure which is below the burn threshold. This is illustrated again in Figure 4 by the vertical set of symbols at the extreme left side of the graph. The closest we come to coagulating the retina is when rhodopsin is bleached, although a safety factor of 60 is indicated. However, in some experiments reported recently by Miss Miller[6] even greater bleaches were effect with white light and, despite careful filtering of infra-red, the retinal exposures fell short of coagulation by a factor of only about 30. Precisely how safe these "safety factors" are is speculative, but our confidence in them may be misplaced in view of the findings reported by Weale[17] and Dollery[9].

It has been noted previously that the thresholds for flash blindness (to the 90% bleaching level) and retinal burn with the ruby laser are reached with very nearly the same retinal radiant exposure. But for the gallium arsenide laser, the burn threshold is greatly exceeded before a flash-blinding effect is produced. Proceeding to the extreme case - the neodymium laser - Figure 4 shows that cooking takes place long before a marked visual effect can be produced. In fact, the neodymium laser appears to be usable (and reasonably safe) in vision studies only for the determination of absolute thresholds at $\lambda = 1060$ mμ .

In conclusion, the obvious corollary to this analysis bears mention. In the design of protective devices, it is important to recognize that protection from flash-blindness does not necessarily ensure protection against irreversible retinal injury. Both thresholds must be examined and the lower used in the determination of safety criteria.

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* In these and previous calculations the cone pigments have been treated as a single light-sensitive substance having the absorption characteristics of the photopic spectral sensitivity curve.

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RETINAL RADIANT EXPOSURE (log cal/cm²)
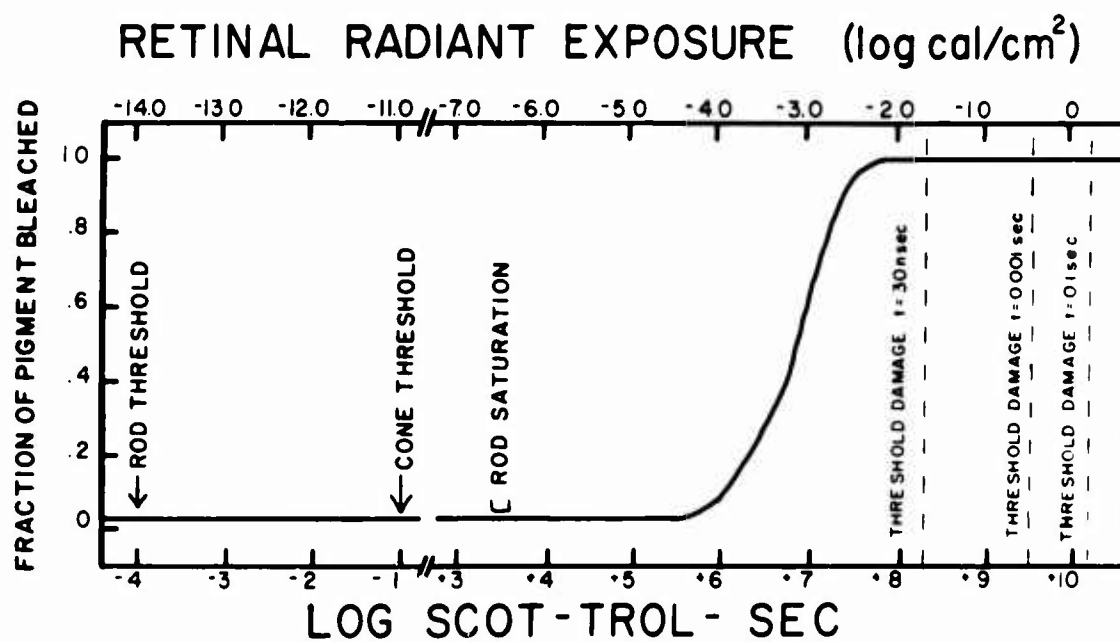

Figure 1

TIME IN DARKNESS (minutes)

Figure 2

Figure 3

Figure 4

IMMEDIATE AND DELAYED RETINAL VASCULAR CHANGES
FOLLOWING EXPOSURE TO HIGH INTENSITY LIGHT

by

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SUMMARY

Exposure of t pig retina to intense unfocussed light from a Xenon
lamp produces immediate and delayed changes in the retina and its
vascular bed. Long exposures (40-240 seconds) cause an immediate whitish
discolouration of the retina. Fluorescence angiograms at this stage show
that intense leakage is taking place from capillaries and small arterioles.
Closure of the smaller vessels takes place in 30-60 minutes but larger
arteries and veins above about 60 μ diameter remain patent at this stage.
After 1-3 days, haemorrhage occurs in the exposed area. Larger arteries
or veins may become occluded and all become tortuous and dilated. The
intensity of these changes is variable and is usually more severe in
animals with deeply pigmented retinae.

Shorter exposures (20-40 seconds) caused no immediate change in the
vessels apart from a few leaking points. Areas of whitish discolouration
appeared after 1-3 days and the larger vessels became dilated and
tortuous. Regions of dilated capillaries appear on angiograms.
Exposures of less than 20 seconds caused no immediate or delayed damage.

Histological observations indicate that patchy retinal necrosis occurs
in the retina exposed for long periods but vascular changes occur in areas
where histological changes are confined to swelling and migration in the
pigment layer. The vascular changes resemble in some respects those
resulting from radiation in other tissues.
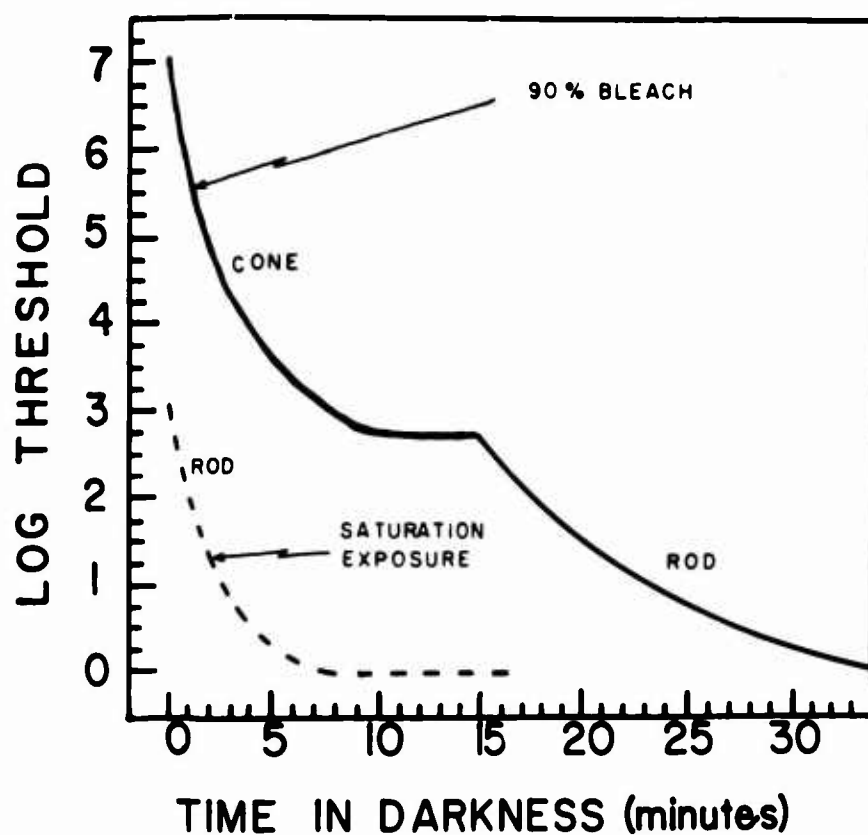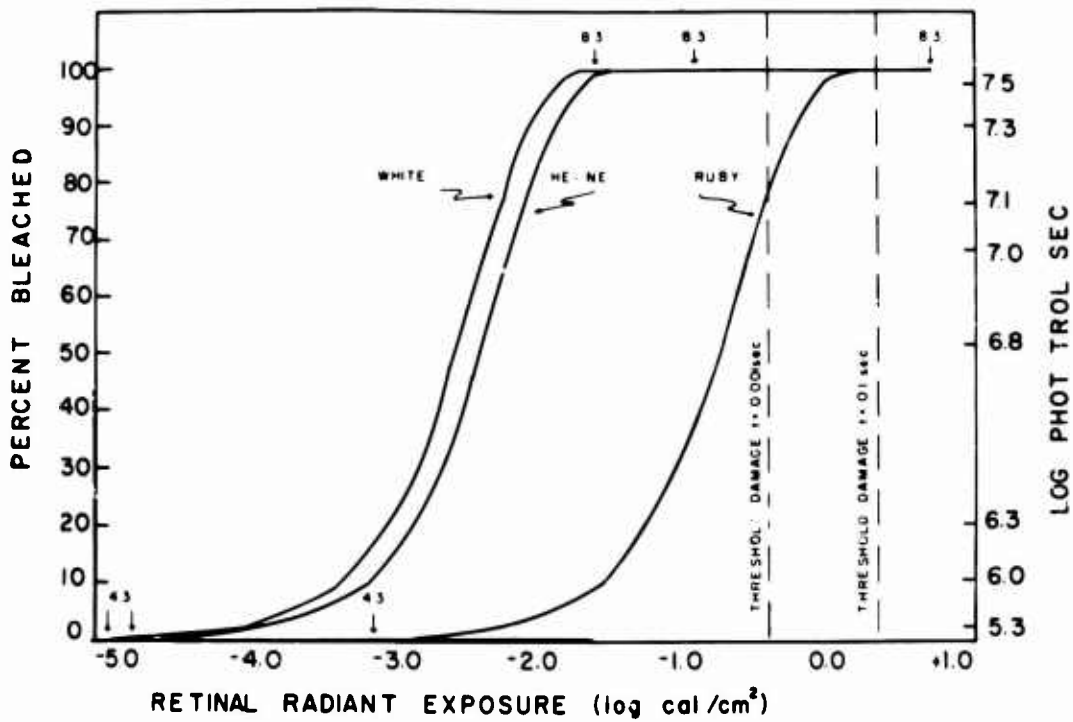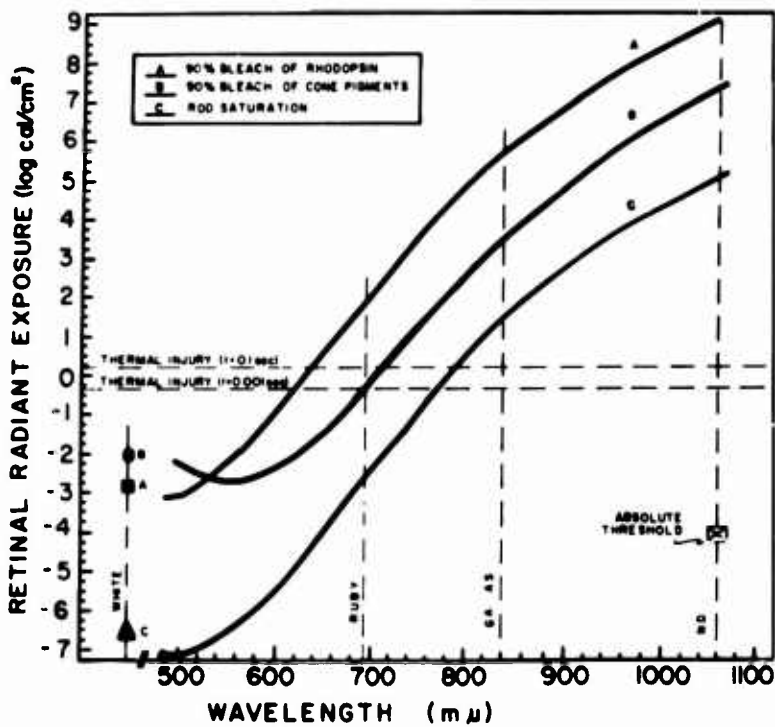
IMMEDIATE AND DELAYED RETINAL VASCULAR CHANGES
FOLLOWING EXPOSURE TO HIGH INTENSITY LIGHT

C.T.Dollery, E.M.Kohner, J.W.Paterson and P.S.Ramalho

INTRODUCTION

The research described in this paper began with a chance observation. During studies of retinal circulatory changes caused by experimental embolisation we were taking cine fluorescence angiograms using an XBO 150W1 Lamp as light source in the retinal camera (Dollery, Henkind, Paterson, Ramalho and Hill, 1965). A deep blue filter as in the light beam and while this remained in place no detectable retinal damage occurred. Withdrawal of this filter for colour cine photography increased the retinal irradiance approximately eight times and a slowly-developing whitish colour change occurred. At this time fluorescence angiograms demonstrated leakage and obliteration of small retinal blood vessels. A series of experiments were designed to evaluate this response and the first results are described in this paper.

Methods

The Carl Zeiss Fundus Camera is a standard optical instrument which incorporates a Tungsten light source for viewing the eye and an electronic flash tube for photography. For cine photography the flash tube was removed and replaced by an XBO 150W1 high pressure continuous-running Xenon lamp. Owing to the intense heat generated, lamp cooling with air blast was necessary.

Colour and fluorescence fundus photographs were taken by standard methods (Dollery, Hodge and Engel, 1963). Fluorescence photographs were recorded using a blue filter (Kodak Wratten 47b) in the light source and a green barrier filter (Kodak Wratten 58) in the film carrier. Injections of 0.3 ml. of 5% sodium fluorescein were made into the carotid artery and pictures taken at 1-second intervals during dye transit. The film used was Ilford H.P.S. (ASA 800) which was force-developed.

Colour photographs are of value for studying arterioles and veins varying in size from about 150 μ near the optic disc down to about 20 μ which are the smallest visible by this means. They are also useful for studying colour changes in the retina in response to injury. Fluorescence angiograms show details of flow through the retinal vessels and allow the individual capillaries to be resolved because of the greater contrast. Abnormal vessels often stand out because dye leaks from them into the surrounding retina.

The animals used were white pigs weighing about 15 kgs. at the time of the first study. Anaesthesia was induced with sodium thiopentone and the animals were then

intubated. Anaesthesia was maintained by inhaled fluothane supplemented by an inspired gas mixture of nitrous oxide and oxygen in the proportion of 2:1.

In each study preliminary colour photographs and fluorescence angiograms were recorded before exposure to high intensity light. These studies were repeated for up to 2 hours after the exposure and some survival experiments were continued for up to 3 weeks. Electronic flash equipment used for recording these photographs does not itself cause any retinal damage.

The retinal irradiance was measured in vitro using a Hilger and Watts Thermopile (FT.4) and a Digital Voltmeter. The irradiance was calculated to be 0.25 calories per square centimetre and the variation of intensity between the highest and lowest areas was 30% above and below the mean. The area of retina exposed to the light was a circle approximately 8.5 mm. in diameter in all experiments.

RESULTS

Twelve pigs were used and a total of 22 separate retinal areas were exposed to the light for periods ranging from 10-180 seconds.

Exposures 10-40 seconds

Six areas in six separate animals were exposed for 30 seconds or less but none showed any immediate or late changes in either colour or fluorescence photographs. Three areas were exposed for 40 seconds and none showed any change on the first day of study on colour photographs. One of these three animals showed leakage of fluorescein from small venous branches beginning 17 minutes after light exposure and steadily increasing so that at one hour there was widespread leakage from small arterioles and venules. Capillaries in the centre of the lesion were obliterated, and at the periphery they leaked dye (Fig.1). Colour studies at this time showed no abnormalities despite the vascular leakage and capillary closure demonstrated on the angiograms. Re-examination of this eye at five days showed an area of haemorrhage. Fluorescence angiograms showed dilated leaking capillaries surrounding the burned area and apparently growing into it. At 10 days the area of haemorrhage was smaller and the main vessels appeared crowded together probably because of fibrosis and shrinkage in the intervening retina.

Exposure for 60 seconds

Seven areas of retina were exposed to the light for 60 seconds and three of these showed no change either early or late. Only one showed an acute change in the colour photographs and this consisted of loss of the normal radial striate markings of the nerve fibre layer with pallor in the centre of the lesion. This animal and one other with a normal ophthalmoscopic appearance showed coarsening of the capillary pattern on an angiogram about 40 minutes after the burn indicating that some capillaries were occluded. There were many leaking points on small vessels. Two other animals which showed no acute changes were restudied at 3 and 7 days respectively. Each had a lesion consisting of three concentric rings of pigmentary disturbance. The outer zone was narrow and pale and inside there was a broader and irregular area with more pigmentation. The central part was depigmented. In one of these animals the entire

area had shrunk and the main artery become more tortuous. All pigs that showed colour changes in the retina on follow-up studies also showed retinal shrinkage with crowding together of the main vessels. In most instances the main artery and vein also became much more tortuous.

Duration 80-180 seconds

An opalescent, whitish discolouration of the retina appeared during the first study in four animals. In one 80-second burn the retina did not become discoloured until 37 minutes after light exposure while for the longest exposure (180 seconds) the white colour was obvious during the period of exposure and within 25 minutes small haemorrhages had appeared in the centre of the lesion. One animal, with a partially albinotic retina, was exposed for 90 seconds and no acute change appeared. Another, which appeared almost totally albinotic, was exposed for 80 seconds and there was some pruning of small vessels on the first day of study; restudy at 4 days and 2 weeks showed an ill-defined irregular area with large scattered lumps of pigment.

Those animals which showed acute changes in the retina on colour photographs all showed profuse leakage of fluorescein from small arterioles and venules, with some obliteration of capillaries. Several days later bizarre vessels, larger in size than capillaries, were visible on fluorescence angiograms forming tortuous loops and anastomotic channels between arteries and veins. Many vessels showed intense dye leakage and no normal capillaries were seen in the centre of the burned area.

Discussion

Several interesting points emerge from this work. Firstly, it is clear that high intensity light may cause severe retinal damage without any change in the ophthalmoscopic appearance during the first hour after exposure. Colour photographs taken several days later may reveal widespread haemorrhage and damage to vessels despite a normal appearance on photographs taken up to an hour after exposure. It appears that the fluorescence method is more sensitive for early detection of retinal damage following exposure to high intensity light than ophthalmoscopic examination. Dye leakage from small blood vessels with capillary obliteration was evident in several retinae when colour studies were normal. Fluorescence angiography should provide a useful tool for further experimental studies in animals and for the investigation of accidental exposure of human retinae to high intensity light.

It is interesting to note the very severe changes that took place in retinal blood vessels both in acute and chronic studies. The most important site of energy absorption in the retina is the pigment layer between the retina and the choroid. However, this layer is some distance away from the retinal blood vessels which should have a useful built-in cooling mechanism in the shape of the blood circulating through them. It is possible that energy absorption of the red cells of the blood, or the walls of the vessels, may be partly responsible for the severe vascular damage. Lack of vascular changes in the albinotic animals which had relatively little pigment is against this explanation. However, the proposition deserves further study as it might make an important difference in the spectral sensitivity of different retinal elements. Ruby laser light would not be absorbed in red blood cells whereas white light would. An alternative explanation for the severe damage to retinal blood vessels is that they are particularly susceptible to thermal damage from heat flowing through the retina from the pigment layer.

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Failure to demonstrate any damage from exposures up to 40-seconds duration and increasing response with increasing duration of exposure thereafter may also have important consequences. It is generally assumed that thermal equilibrium will be reached in different parts of the retina within one retinal circulation time if light exposure is continuous. The long duration of exposure required in these experiments suggest that retinal damage may follow prolonged but slight elevations of temperature. A similar mechanism might lead to a summation effect when the retina is exposed to a sequence of high intensity light flashes, each of which is below the threshold for causing a retinal burn.

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2. Dollery, C.T. Hodge, J.V.   Med. & Biol. Illus Vol.13, 1963, p.4.
   Engle, M.

Fig.1   Fluorescence angiogram of a pig retina taken one hour after exposure to high intensity light for 40 seconds.   Note the many leaking points in the retina. The ophthalmoscopic appearance at this time was normal

A STUDY OF EFFECTS OF LASER IRRADIATION ON HEAD AND EYE

OF SMALL ANIMALS IN TERMS OF NEURO-MOTOR BEHAVIOR

(abridged)

by

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SUMMARY

This exploratory investigation has provided a useful basis for the application of a more classical experimental design and analytical procedures being considered for subsequent investigations. Sufficient evidence was accumulated from this study to postulate that for given laser energies, there will be blindness only if received by tne eye, but instant lethality if received on the top of the head. Thus for higher energy accident probabilities, it becomes imperative to protect the head.

A methodology is suggested for simulating serious eye and neuromotor defects in order to evaluate their probable influences on performance in association with defined tasks.

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INTRODUCTION

It is clear that accidental laser irradiation may cause a wide range of injuries
to the eye up to and including total impairment. While such studies associated with
this range of pathology are important for effective determination of types and modes
of protection for minimizing or preventing these consequences, it is also important
to consider the effects of similar irradiation on other vital body regions. It goes
without saying that as the striking energies likely to cause accidental damage
increase, so will the magnitude of the protection problem.

Since the onset of studies regarding the biologic effects of laser irradiation,
the most sensitive organ tissue has been shown to be the retina of the eye. The
minimal energy necessary to just produce a grossly visible lesion on the retina has
been established at 0.72 joules per square centimeter in 200 milliseconds or 0.07
joules per square centimeter in 30 nanoseconds[2].

The concept of selective absorption by various tissue components to specific
wavelengths has been discussed and related to skin, blood, and particularly the
retina[1,3]. Ocular transmission of various wavelengths has also been studied[2].
Ham, *et al.* have discussed the energy levels necessary to produce minimal lesions in
the retina of the rabbit[2]. Variations among albino, brown, and black animals were
noted. However specific criteria have not been established for predicting relations
between energies and pathologies for the small animals.

Laser energy levels near damage threshold values have been used for purposes of
photocoagulation[5]. The lesions produced are not unlike nuclear flash spots or eclipse
burns[4]. The ocular hazard of greatest concern at present is closely related to the
intentional lesion produced by a laser to 'weld' a detached retina. At this energy,
the greatest physiological damage occurs when all or a part of the fovea is destroyed.

There have been several demonstrations of complete destruction of the eye by large
energy densities. These have not been systematically analyzed nor have any neuro-motor
effects been noted following this path of entry. The major pathologic effect is an
explosive lesion of the retina with ensuing hemorrhage into the vitreous. The
result is that of sudden, complete blindness in that eye.

This study was conceived to investigate a range of response-dose-time relations
of importance for eye and head as sites of accidental injury. It was believed that

once such a range could be identified, a prediction function or model could be generally useful in an evaluating protective devices on a quantitative basis.

METHODS

The purpose of this experimental study was the determination of a range of important responses in terms of neuro-motor activity from nil to lethality for laser irradiation focused on the head and eye of small animals, namely, mice, rats, and guinea pigs.

Following each application of laser irradiation, the animal specimen was removed and observed for lethality and/or level of neuro-motor activity up to one hour after injury. The immediate postinjury behavior was recorded using 35 mm motion pictures. Essentially the same procedure was used for the ocular tests. Although the animals were weighed as a routine procedure, weight was not considered as an important parameter in this investigation.

Experimental Design

Inasmuch as this was a pilot type of study with no formal statistical experimental designs chosen for hypothesis testing, attention was directed at the acquisition of statistical sensitive data that would lead to hypothesis generation.

Instrumentation

The laser used in this experiment was a Raytheon No. NH 102 ruby laser liquid nitrogen cooled with an output wave length of 6934 Å. Its energy range is from 15 to 200 joules and its pulse duration is 2.7 milliseconds. It has a minimum spot diameter of 0.6 millimeter. The ruby is 6 in. in length and 5/8 in. in diameter.

The head has four interlocking elliptical cavities with the ruby mounted at the common foci and an FX 47 xenon flashlamp at each of the other 4 foci. The ruby rod is conductively cooled to liquid nitrogen temperature through the ruby holders. Each lamp can be driven by 32,000 joules stored in capacitor banks charged to 3 kilovolts.

RESULTS

The data collected so far for this exploratory investigation are given in Tables I through III. Since we are only concerned with three parameters in each study, namely, *dose*, *time* and *response* (in terms of either *mortality* or *level of neuro-motor activity*), the data are also presented in three-dimensional form as shown in Figures 1 to 3.

Studies were initiated in terms of both mortality and neuro-motor activity resulting from applications of focused laser energy to the eye of these small animals. It was obvious immediately that lethality from eye shots was difficult to obtain without going up to doses 500% and more than that applied to the head. While we have obtained lethality in the 180-200 joule energy level directed at the mouse eye, we had not repeated the exercise under more controlled conditions due to laser maintenance difficulties. Essentially, the same experience was had with the rats and guinea pigs.

Somewhat more information was obtained for neuro-motor activity studies. Table I shows the results for eye shots in the white mice. For statistical statements we need considerably more data. However, we do observe that very little neuro-motor deficit was attained for energies even up to 125 joules. There was, of course, complete loss of vision from the injured eye along with considerable hemorrhage.

In the case of eye shots in the white rats, we observed no neuro-motor activity decrement for energies up to approximately 110 joules. Here also we need to gather more samples at higher dosage levels to make adequate comparisons. Table II shows the results of the eye shots on the rats. Essentially the same situation exists for the eye shots on the guinea pigs, i.e., higher dosage levels are needed. Table III shows the data on the guinea pigs.

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TABLE I

Mice – Eye Shots: Using Ruby Laser Focused 2-3 Millimeters Deep to Pupillary Region of Eye

Neuro-Motor Activity Study

Response: To One Hour After Injury

Dose in Joules	Weight in Grams	Levels of Activity*	Time Postinjury in Minutes	Remarks
54	30	1	Immediately	Profuse bleeding from eye
		0	9	No more bleeding
		0	60	
91	26	0	Immediately	Moderate bleeding from eye
		0	60	
124	27	3	Immediately	Moderate eye bleeding
		3	2	
		1	3	
		0	60	

* Descriptions of Levels of Activity:

0 – No apparent abnormality in neuro-motor activity.

1 – Reduced but controlled neuro-motor activity.

2 – Reduced control of neuro-motor activity (loss of fighting ability ...)

3 – Complete loss of neuro-motor activity (twitching, convulsing ...)

4 – Inactive and unconscious.

5 – Dead.

TABLE II

Rats – Eye Shots: Using Ruby Laser Focused 2-3 Millimeters
Deep to Pupillary Region of Eye

Neuro-Motor Activity Study

Response: To One Hour After Injury

Dose in Joules	Weight in Grams	Levels of Activity	Time Postinjury in Minutes	Remarks
62	128	0	Immediately	
		0	6	
		0	60	
72	120	0	Immediately	Internal eye hemorrhage
		0	2	
		0	60	
107	103	0	Immediately	
			3	
			60	

TABLE III

Guinea Pigs – Eye Shots: Using Ruby Laser Focused 2-3 Millimeters Deep to Pupillary Region of Eye

Neuro-Motor Activity

Response: To One Hour After Injury

Dose in Joules	Weight in Grams	Levels of Activity	Time Postinjury in Minutes	Remarks
105	270	0	Immediately	
		0	38	
		0	60	
117	232	0	Immediately	
		0	1	
		0	60	
119	230	2	Immediately	
		2	2	
		1	15	
		1	60	
120	226	2	Immediately	
		1	3	
		1	60	
121	247	2	Immediately	Some
		1	5	bleeding
		0	60	from nose
126	238	1	Immediately	
		0	60	
128	227	2	Immediately	
		2	1	
		1	60	

Fig.1 Laser irradiation directed at eyes of white mice and focused 2-3 millimeters below cornea surface (dose-time-neuromotor relations: to one hour after injury)

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Fig. 2 Laser irradiation directed at eyes of white rats and focused 2-3 millimeters
below cornea surface (dose-time-neuromotor decrement relation:
to one hour after injury)
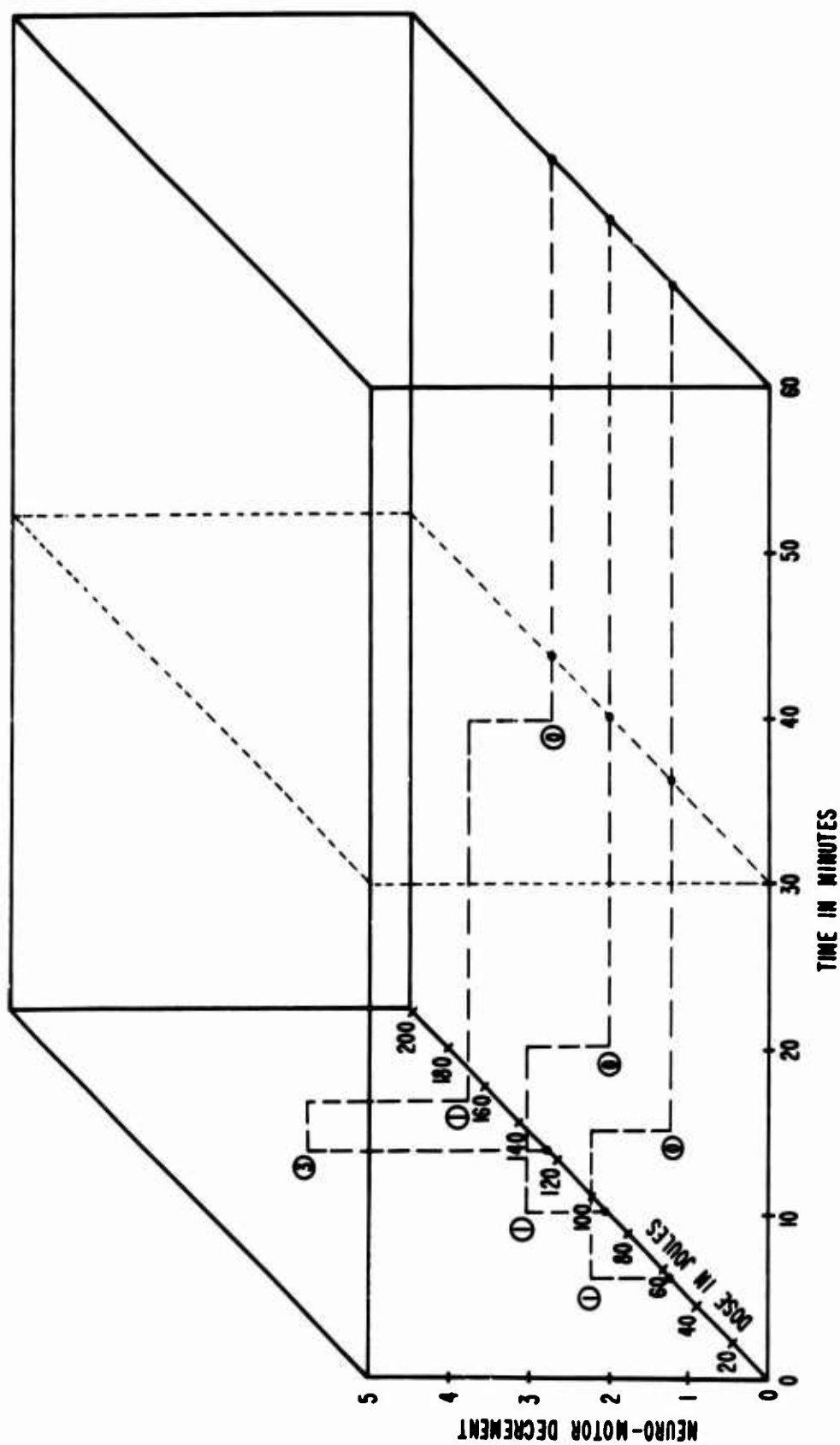
Fig.3 Laser irradiation directed at eyes of white guinea pigs and focused
2-3 millimeters deep to cornea (dose-time-neuromotor relation:
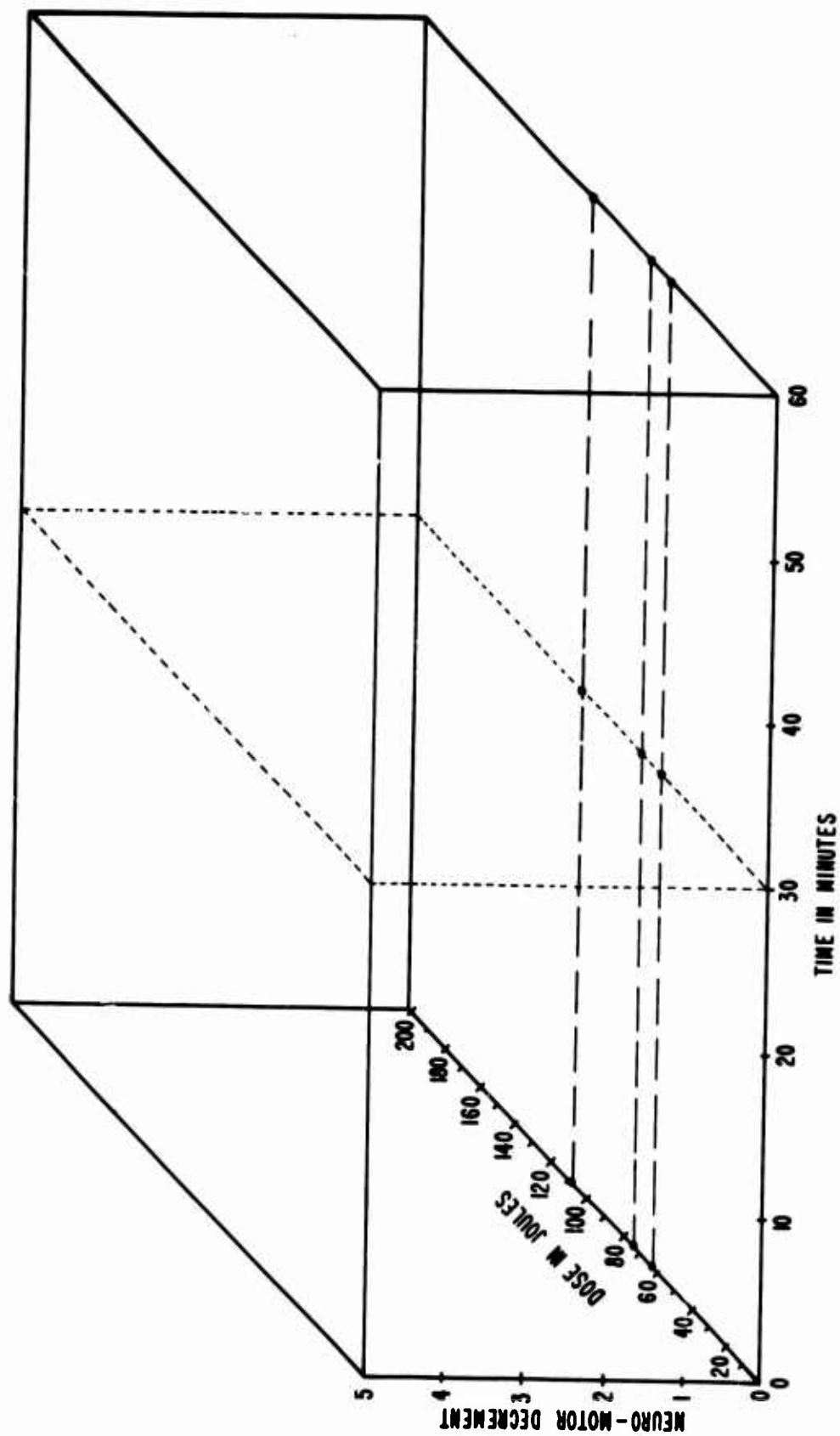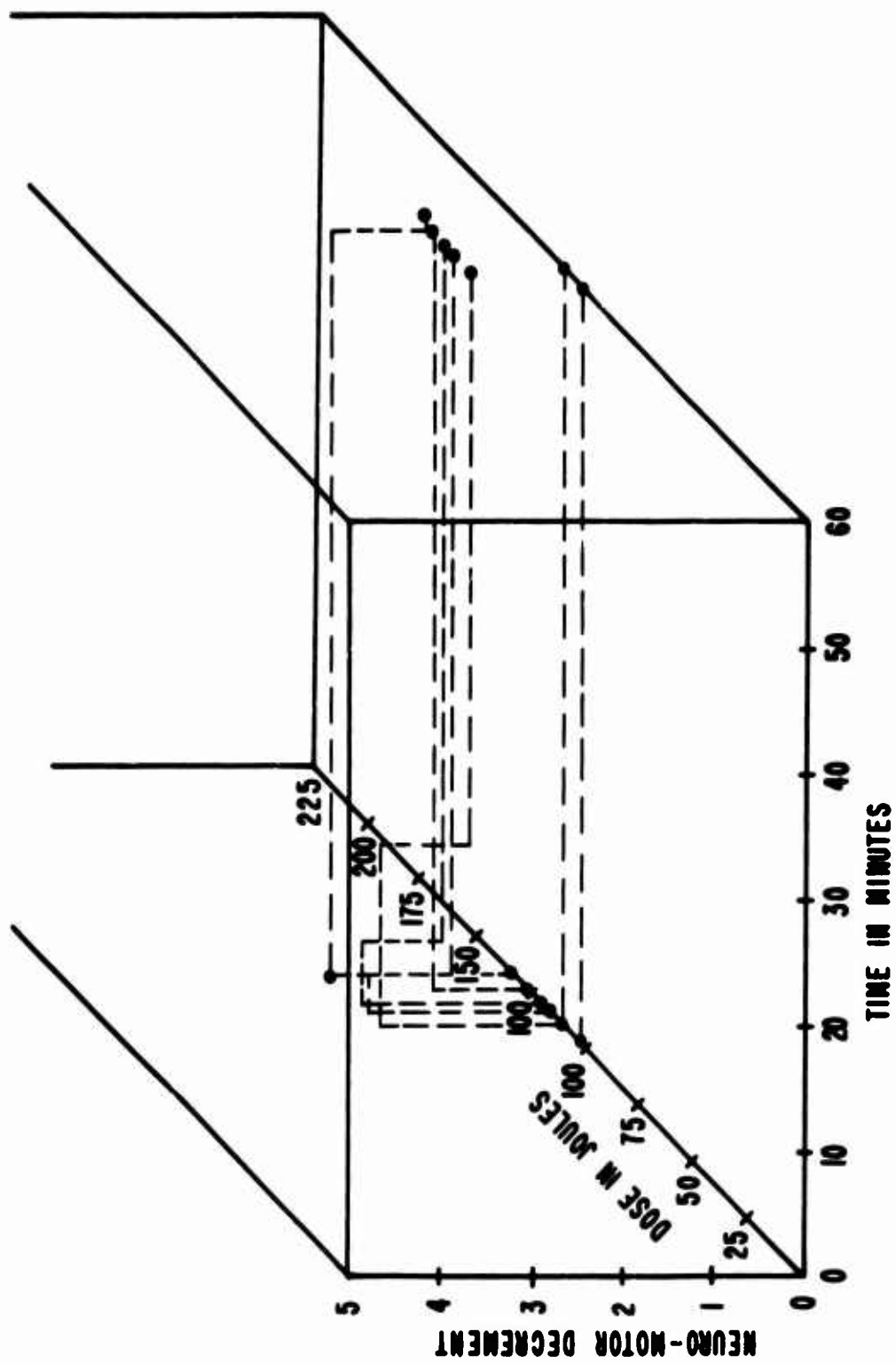to one hour after injury)

FUNCTIONAL EFFECTS

AND PROTECTION

THE TIME COURSE OF FLASH BLINDNESS

by

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SUMMARY

Flash blindness must be measured in relation to visual tasks demanded
in a given situation. Its duration depends on the method of measurement
as well as the physical characteristics of the blinding exposure.   This
paper reviews the quantitative laboratory studies which have been performed
to investigate the effects of: flash luminance, duration, and spectral
character; visual acuity requirements of the criterion visual task;
illumination provided for the criterion task; and relative positions of
retinal images of the task and the flash. Effects are measured in terms
of elapsed time between flash exposure and satisfactory performance of
the task. Results show that illumination of the task is in most cases
the most significant variable. By increasing task luminance, recovery
time can be reduced to two or three seconds for flash exposures which do
not cause retinal injury.

THE TIME COURSE OF FLASH BLINDNESS

John Lott Brown

INTRODUCTION

The time course of flash blindness is not determined absolutely by the physical characteristics of the energy which produces the blindness.. Blindness must be measured relative to some desired visual function for any of the various possible conditions which may produce it. The specific criterion which is selected as a basis for measurement is an extremely important variable in the determination of the time course of flash blindness. For conditions of a blinding flash short of those which may cause irreversible injury, the characteristics of the test criterion may prove more important than the flash characteristics.

The interrelations of physical parameters of both the blinding flash and the test criterion are of considerable importance in influencing the way in which recovery progresses. A study of these interrelations provides a basis for the selection of the most efficient practical approach to the problem of providing protection against flash blindness.

TOTAL ENERGY OF THE BLINDING FLASH

If we neglect for the moment some of the complications which may arise from variations in the temporal distribution of the energy of a blinding flash, it is possible on the basis of certain logical considerations to make predictions as to the overall form of a function which relates recovery time following exposure to a blinding flash and blinding flash energy. Such a relation is illustrated in Figure 1. A subject is required to signal by an appropriate response when he is able to detect some element of information in the visual environment, as an indication that he has recovered from a blinding effect. For the condition where flash energy is so low that it has a negligible effect on the visual system, the response time will be of a finite duration equivalent to the simple visual reaction time. As the energy of the flash increases on a logarithmic scale, it can be predicted that the recovery time will increase at an increasing rate. The effect will become appreciable when flash energy reaches levels which cause bleaching of significant amounts of retinal pigments.

It is reasonable to assume that the increase in recovery time will reach a maximum rate and then decline as bleaching energy approaches a level where total photopigments available are nearly depleted. This effect may result in a plateau of recovery time if the total depletion of available photopigments occurs in advance of actual injury to the retina. With the onset of injury, we may expect further increase of recovery time, approaching infinity along an asymptote marked by that level of flash energy for which there is irreversible injury to the retina.

A number of laboratory experiments have been performed which provide support for various portions of the hypothetical curve presented in Figure 1. Metcalf and Horn employed a 17-minute test flash at a luminance of 0.07 ft.-lamberts which flashed on and off at one second intervals as a criterion of effect. The results of their experiment are shown in Figure 2 for each of four subjects. Although the data are plotted such that they show a variation in illumination for regularly increasing recovery times, it is evident that recovery time is increasing at an initially decreasing rate, followed by a possible increase in rate for illuminations of 5,000 lumens per square foot or more. This corresponds to a recovery time for the conditions investigated of approximately 85 to 90 seconds.

Miller, using a test criterion composed of Snellen letters, found similar results over a similar range of adapting flash conditions. In a presentation of the logarithm of recovery time as a function of the logarithm of adapting flash energy, the relation-ship was fitted by a straight line. This corresponds to the portion of the curve in Figure 1 where recovery time is increasing at an increasing rate.

Whiteside has presented data from several experiments which illustrate a portion of the curve in Figure 1 where recovery time approaches a plateau and then shows a subsequent further increase (Fig. 3). Additional results obtained by Hill and Chisum are presented in Figure 4. There are data for each of three levels of illumination of the test criterion, a grating pattern which required a visual acuity of approximately 0.33. The solid and dashed curves for each of the criterion luminance levels represent results for each of two flash durations. (Flash duration will be considered in a subsequent section.) Recovery time increases at an increasing rate with an increase in the logarithm of adapting flash energy, particularly for the lowest criterion luminance. There is a clear indication that recovery time levels off at the highest level of adapting flash energies which were investigated.

THE CRITERION OF FLASH BLINDNESS

It is clear from the data in Figure 4 that illumination of the test criterion is a highly significant variable in determining the time course of flash blindness. This parameter has been studied over a fairly wide range as illustrated in Figure 5. With an increase in the logarithm of display luminance, recovery time (perception time) decreases at a decreasing rate. The families of curves represent six different adapting flash energy levels. Differences in recovery time related to differences in adapting flash energy at low levels of criterion illumination virtually disappear when criterion illumination is elevated. Data are presented for each of two acuity levels. The criterion of recovery was detection of a grating pattern orientation. Two gratings were used, requiring visual acuities of 0.26 and 0.08. The steep drop in recovery time for the higher visual acuity may be attributed to the fact that the luminance threshold for visibility of this grating pattern was close to the lowest display luminance investigated. At this display luminance, recovery time was approaching an infinite value. Miller has presented similar data on recovery time versus the luminance of her letter criterion. In Figure 6 the logarithm of recovery time is shown as a function of the logarithm of test letter luminance. On the coordinates employed, these results show excellent agreement with the results presented in Figure 5.

The single hypothetical curve which is presented in Figure 1 has been generalized in Figure 7 to illustrate the effect of employing a variety of criterion test luminances. The higher the test luminance the faster the recovery time and the more rapid is the initial response at a very low level of adapting energy. The curves in Figure 7 all reach a plateau at approximately the same time, corresponding to a depletion of available photopigment. Each of the curves approaches an infinite recovery time at the same adapting flash energy, i.e., that energy level at which irreversible retinal injury occurs.

By an extension of the results presented in Figure 5, it is evident that if the visual acuity requirements of the criterion test are reduced systematically, there will be a regular change in the form of the functions which relate recovery time to the logarithm of criterion test luminance. Maximum recovery times will be approached at lower and lower test luminances corresponding to the decrease in minimum threshold with decreasing acuity. The lower the acuity the lower will be the test luminance at which recovery time can be measured and the more gradually will recovery time drop to a minimum level as test luminance is increased. At the highest test luminance differences in visual acuity will play little if any role in the determination of recovery time. Thus, the level of illumination of the test criterion will be critical in determining the relation between recovery time and visual acuity. At high luminances, the function will be nearly horizontal with little if any change in recovery time as visual acuity is increased. This will be true so long as the maximum acuity level of which the subject is capable is not exceeded. At lower levels of test illumination, recovery time will increase with increasing acuity at an increasing rate. This effect will be accentuated for higher energies of the blinding flash. Miller has presented results which show the relation between recovery time and visual acuity for each of four adapting flash energies and for a single level of test illumination (Fig. 8). Visual acuity ranged from approximately 0.12 to 0.30. The relation can be fitted by a straight line with recovery time on a logarithmic scale. On an arithmetic scale recovery time would increase at an increasing rate and this would be more marked the higher the adapting flash energy.

DURATION OF THE ADAPTING FLASH

There is evidence that for extremely short adapting flash durations, the bleaching effect will not be as great as that which would occur for the same or even lesser amounts of light energy spread out over a greater time interval. Thresholds measured after a short adapting flash may therefore not be elevated as much as those after a longer duration. This is explained by the fact that a portion of certain unstable intermediate products of bleaching is isomerized back into photosensitive forms by light itself. As exposure is prolonged these are rebleached, a lesser portion returns to a photosensitive form, and so on until maximum bleaching is reached. There appears to be a critical adapting flash duration of approximately 1 millisecond. For shorter durations a given adapting flash energy will cause a lesser amount of flash blindness than the same energy distributed over an interval longer than 1 millisecond. The results of Hill and Chisum may reflect this kind of an effect. The fact that Miller did not find it in her investigation may be tentatively attributed to the fact that she did not employ adapting flash durations much in excess of 1 millisecond. She was unable to do this because of restrictions imposed by her apparatus. It would be most desirable to investigate this phenomenon further in relation to flash blindness.

SPECTRAL CHARACTERISTICS

The spectral variable is one which has been studied only to a limited extent. There may be advantages to be gained by employing a spectral distribution of cockpit illumination which differs significantly from the spectral distribution of the adapting flash in order to take advantage of spectrally selective adapting effects. When colored goggles are worn continuously, both the adapting flash energy and the cockpit illumination will be influenced. Appropriately selected goggle characteristics will reduce adapting flash energy to a greater extent than cockpit illumination. Optimum spectral distribution for the transmittance of goggles or for cockpit illumination will depend, at least in part, on the extent to which visual tasks require photopic, mesopic, or scotopic function. This in turn will depend on the visual acuity requirements of the task. Under daylight conditions, photopic conditions may be expected to prevail. The effects of employing goggles of 1% transmittance with a variety of spectral characteristics are shown in Figure 9. The value of wearing goggles of the kinds represented appears to bear a relation to the acuity level of the test criterion.

It is impossible here to go into a detailed analysis of the interactions of adapting flash energy, criterion test acuity and illumination and spectral characteristics of flash and task illumination. Suffice it to say that the inter-relations of these variables are complex. An additional consideration in the use of goggles is the matter of pilot acceptance. Red goggles might under certain conditions appear to be valuable. Alterations in contrast relations within the visual world seen through red goggles are so great, however, that pilots find them unacceptable. On the other hand, goggles which employ a gold filtering element are acceptable. The spectral transmittance of this material has much less observable effect on contrast relations. Miller has shown that gross reduction of energy in the adapting flash outside of the visible spectrum (infra red) does not alter recovery from flash blindness for energy levels below those which cause retinal burns.

SPATIAL RELATIONS

A decrease in recovery time with an increase in the area of the test flash has recently been reported by Miller. This effect is difficult to interpret, but may reflect complex retinal interactions which occur in the region of an edge or sharp discontinuity of illumination. Haines has recently reported an investigation of the visibility of a moving point source in the presence of a glare source for various relative locations of these in the visual field.

CONCLUSION

It is evident, when the material presented here is compared with the preceding discussions of operational problems, that conditions studied in the laboratory are highly artificial. It must be emphasized that the value of these experiments is to indicate the nature of functional relations among the relevant variables. A knowledge of these relations provides a basis for identifying those variables, the manipulation of which can most efficiently afford protection in a practical situation. Conditions which prevail in the field are far more complex than those in the laboratory and it is not practical to attempt to find relations such as those presented here from field

studies. Values of recovery times reported in laboratory studies should not be considered to have an absolute application to field situations. Whiteside's analyses suggest that recovery times under field conditions may be more rapid than those measured in the laboratory. Laboratory studies emphasize the worst possible conditions, with the test criterion presented directly in the middle of that region of the retina upon which the image of the adapting flash has been centered.

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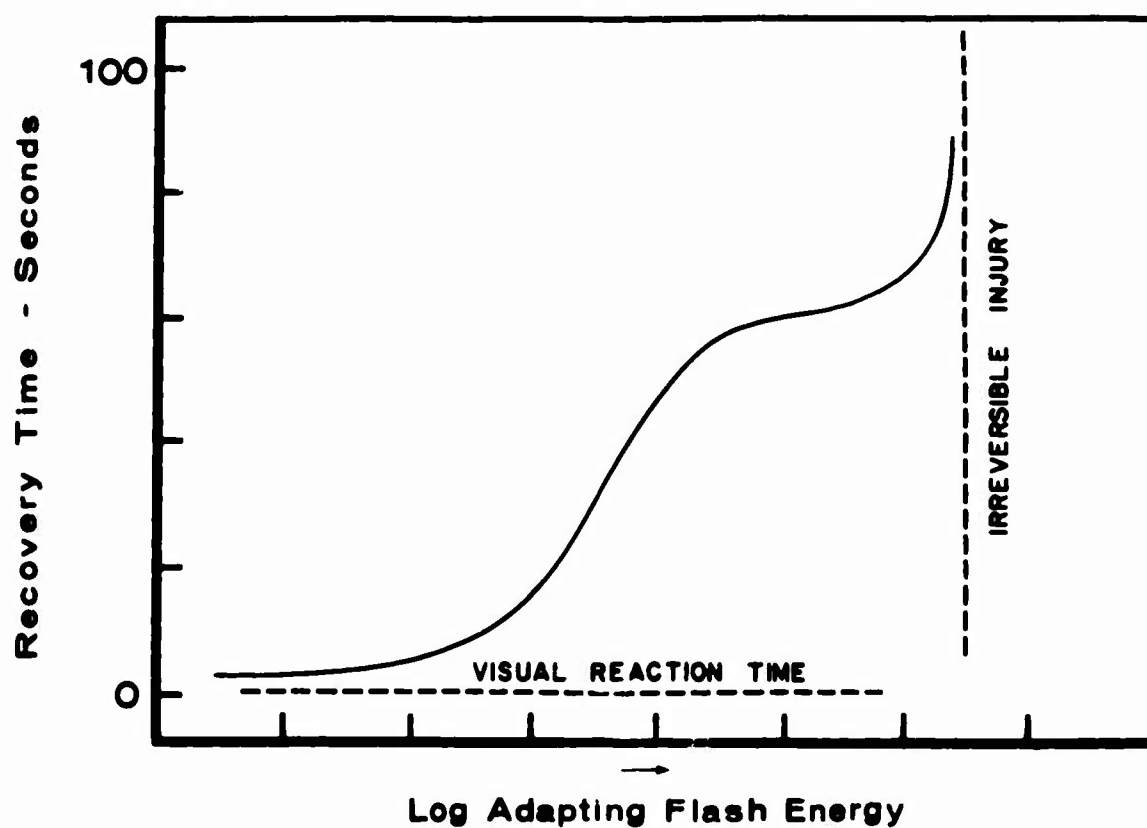
Fig.1 A hypothetical curve illustrating the relation between energy of a blinding
flash and time required for detection of information in a visual display.
The minimum detection time at low flash energy corresponds to visual
reaction time. Detection time approaches infinity as flash energy
approaches a value which will cause irreversible injury

100
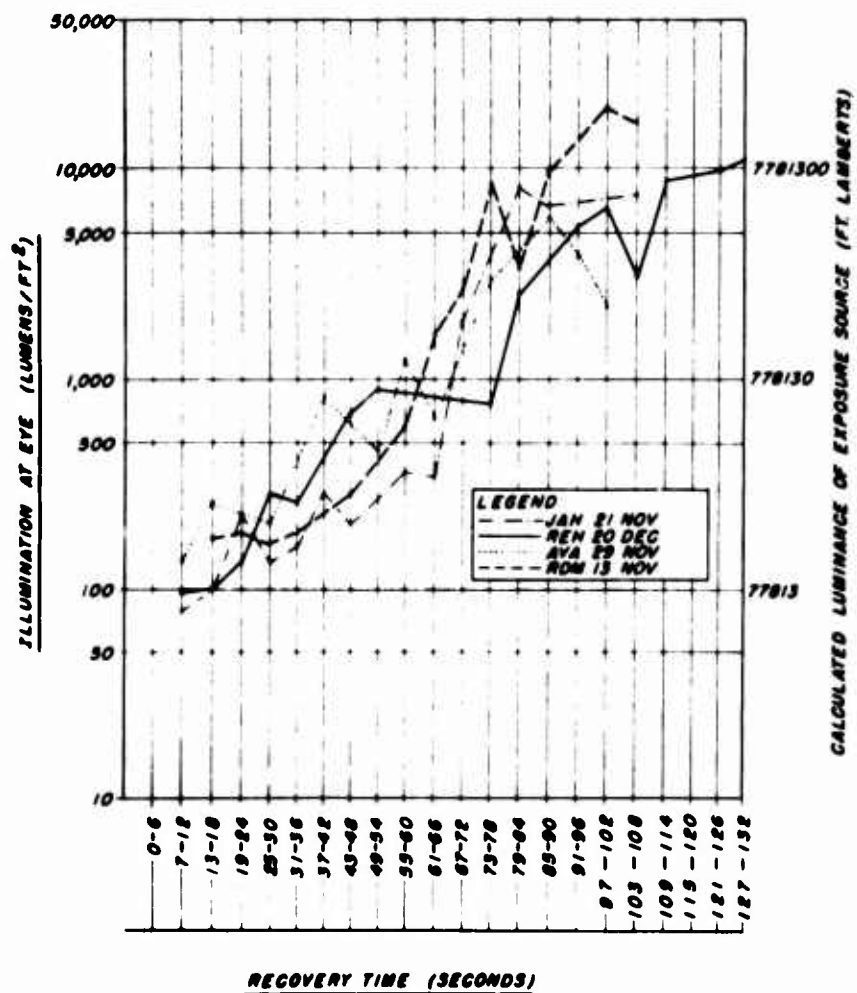
Fig. 2   Time required for detection of a 17-min. circular test patch at a luminance of 0.07 ft-L as a function of the luminance of an adapting flash. Mean values for each of four observers (Metcalf and Horn, 1958).   (1 ft-L = 3.426 cd/m².)
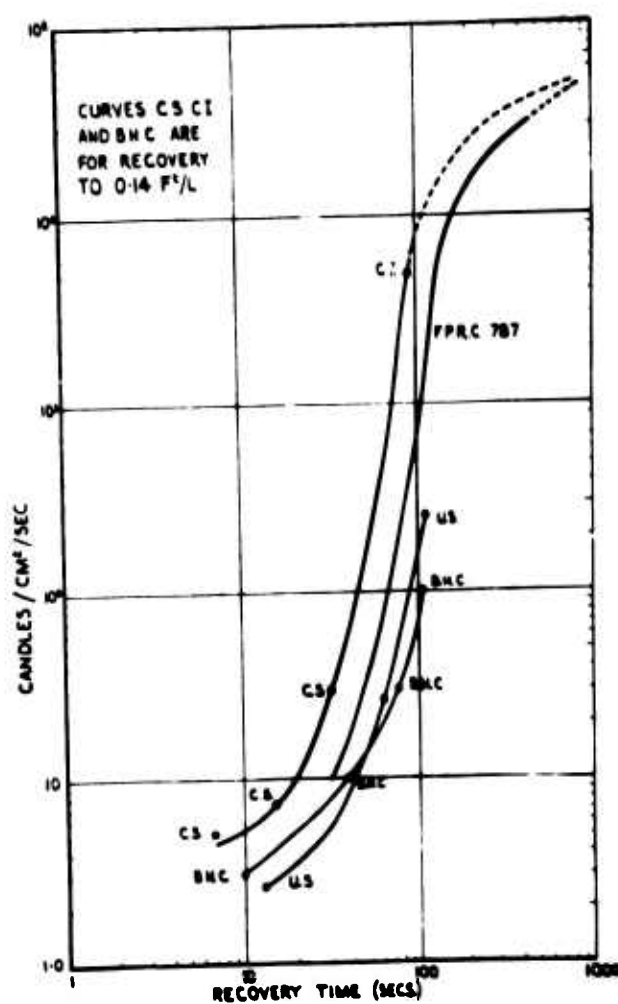
Fig. 3   Recovery times for detection of criterion targets after exposure to an
adapting flash as measured by several investigators. BHC curve was
obtained by Crawford with a 0.14 ft-L target. US curve represents the
data of Metcalf and Horn. Other data were obtained by Whiteside
(Whiteside, 1960). (1 cd/cm^2 = 10^4 cd/m^2.)
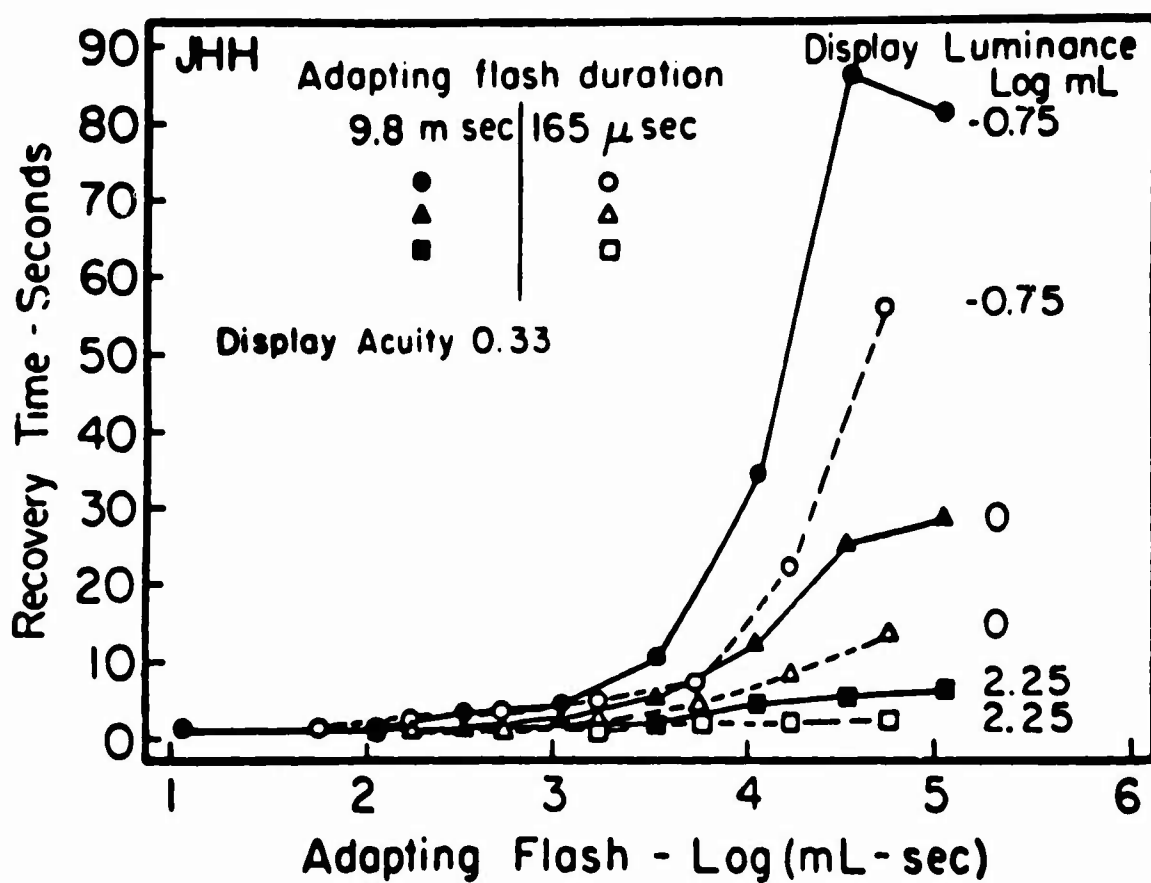
Fig. 4   Time required to perceive an acuity target as a function of the energy of the
adapting flash (log mL-sec). Individual curves represent each of two
adapting flash durations for three acuity target illuminations (Hill
and Chisum, 1962).   (1 mL = 3.183 cd/m².)
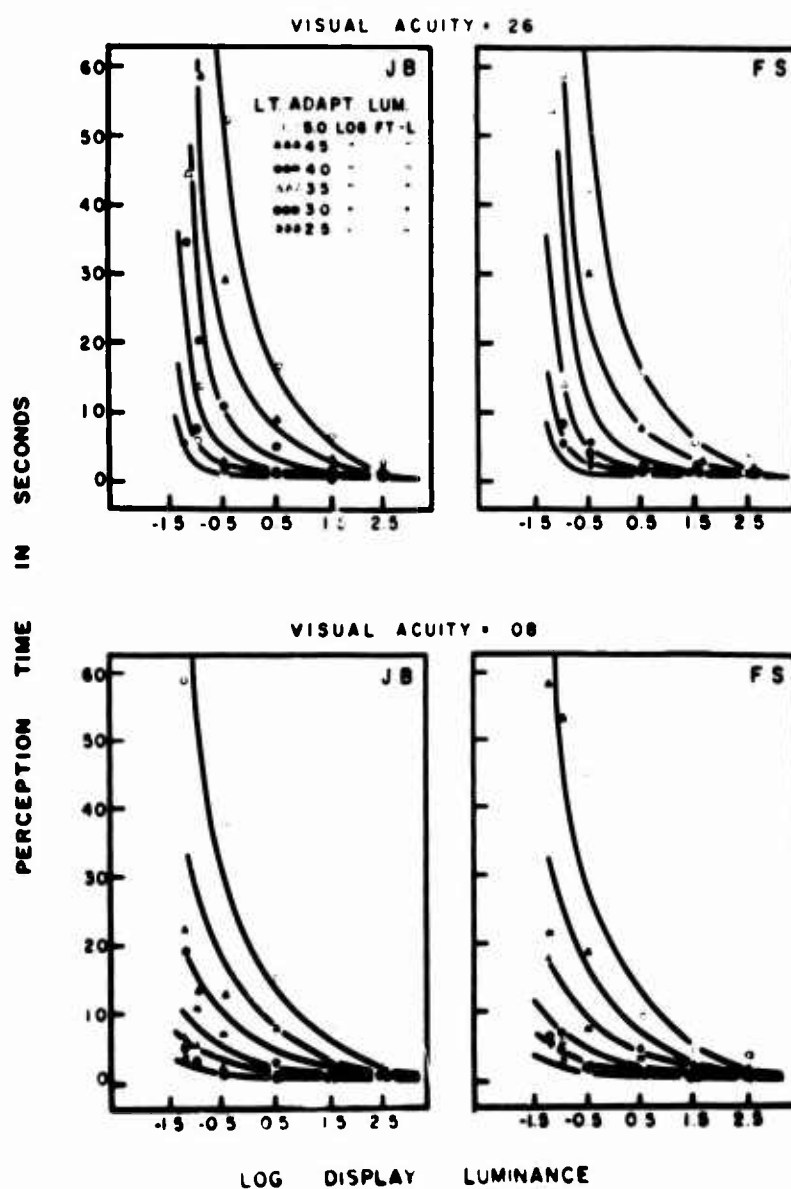
Fig. 5 Relations of perception time to log display luminance (ft-L) for each of 6
adapting flash luminances. Upper graphs represent a grating display
which required a visual acuity of 0.26; lower graphs represent a visual
acuity of 0.08. Subjects JB and FS (Brown, 1964). (1 ft-L = 3.426 cd/m².)

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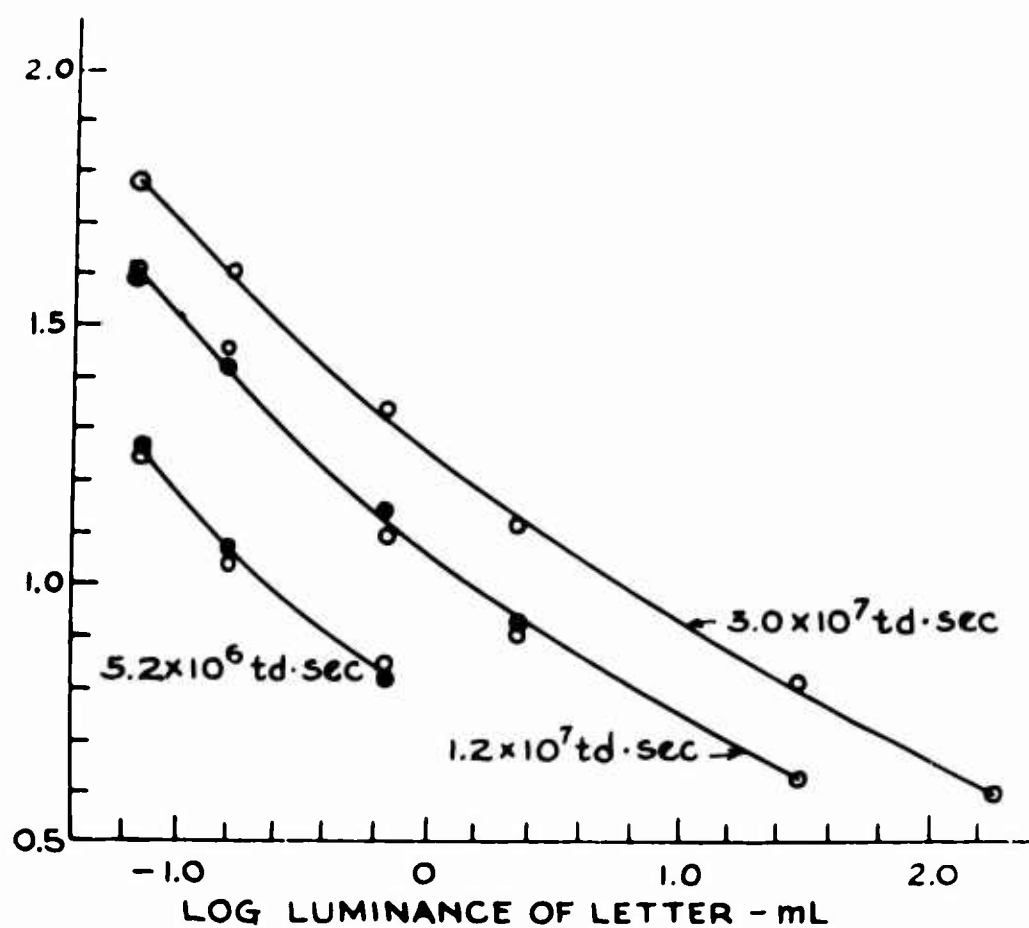
Fig. 6 The relationship between the logarithm of the recovery time and the logarithm of the test-letter luminance for different flash energies. The open circles are the data for 1.4-msec flashes of various luminances and the solid dots are the data for 4.0×10^5-L flashes of various durations. ($1 \text{ mL} = 3.183 \text{ cd/m}^2$.) Miller, 1965
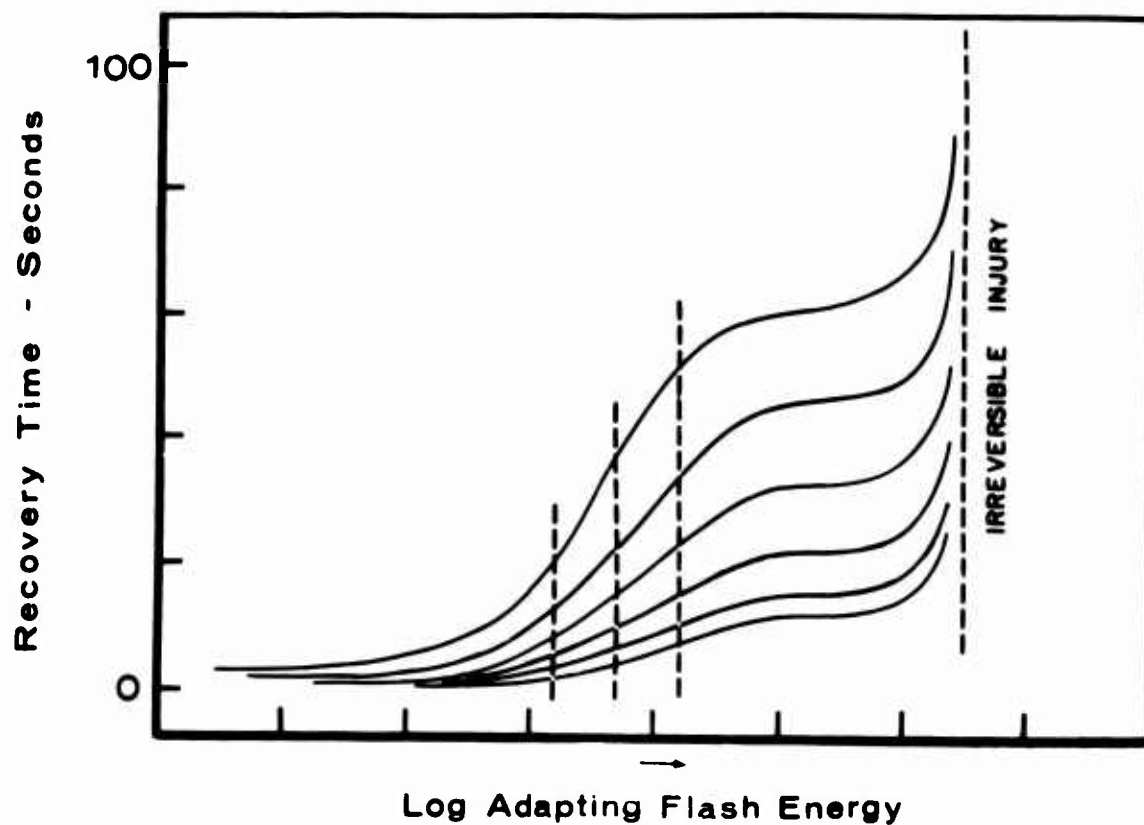
Fig.7 Hypothetical functions like that in Figure 1 for various luminances of the display. Display luminance is assumed to increase in equal logarithmic steps from a low value for the top curve to a high value for the bottom curve

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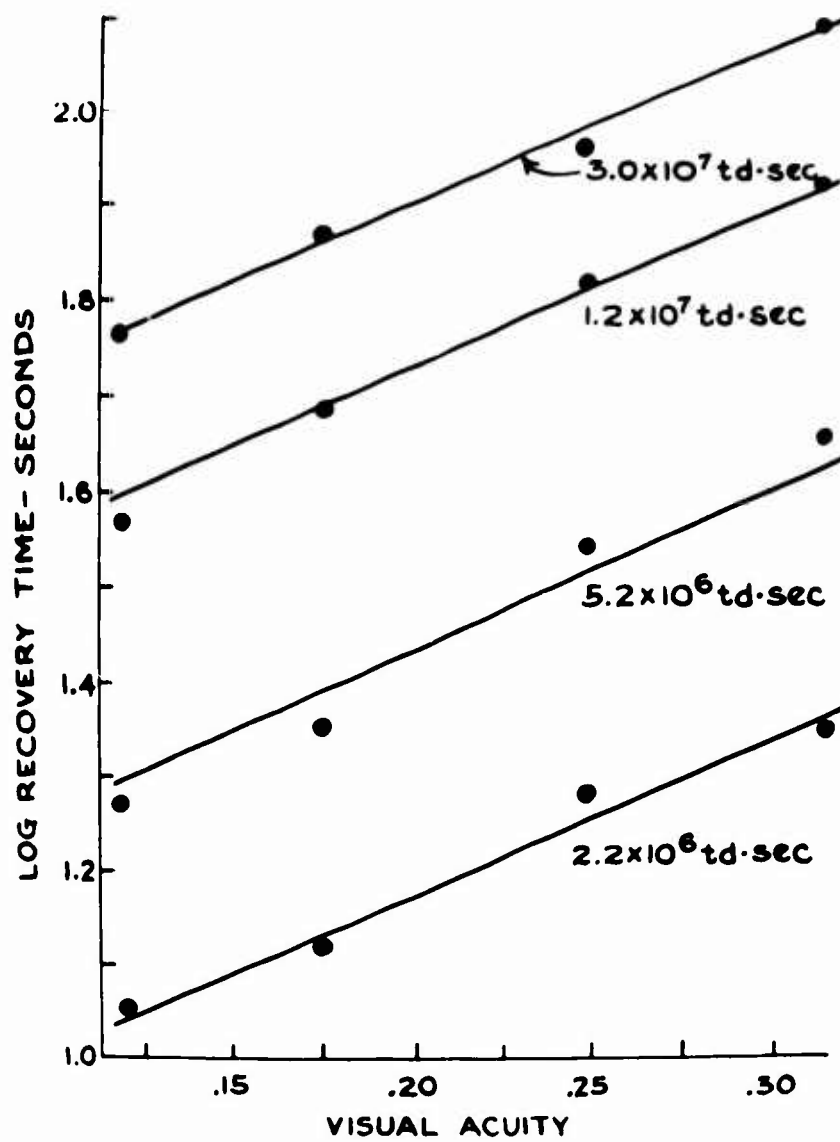
Fig. 8   The effect of target size on recovery time following various flash energies.
The four test letters used subtended visual angles of 42 min, 28.7 min,
20.4 min, and 16.3 min.   The visual acuity is the reciprocal of the
critical detail of the letters in min. of arc.   (Miller, 1965)

DISPLAY LUMINANCE - LOG FT. LAMBERTS
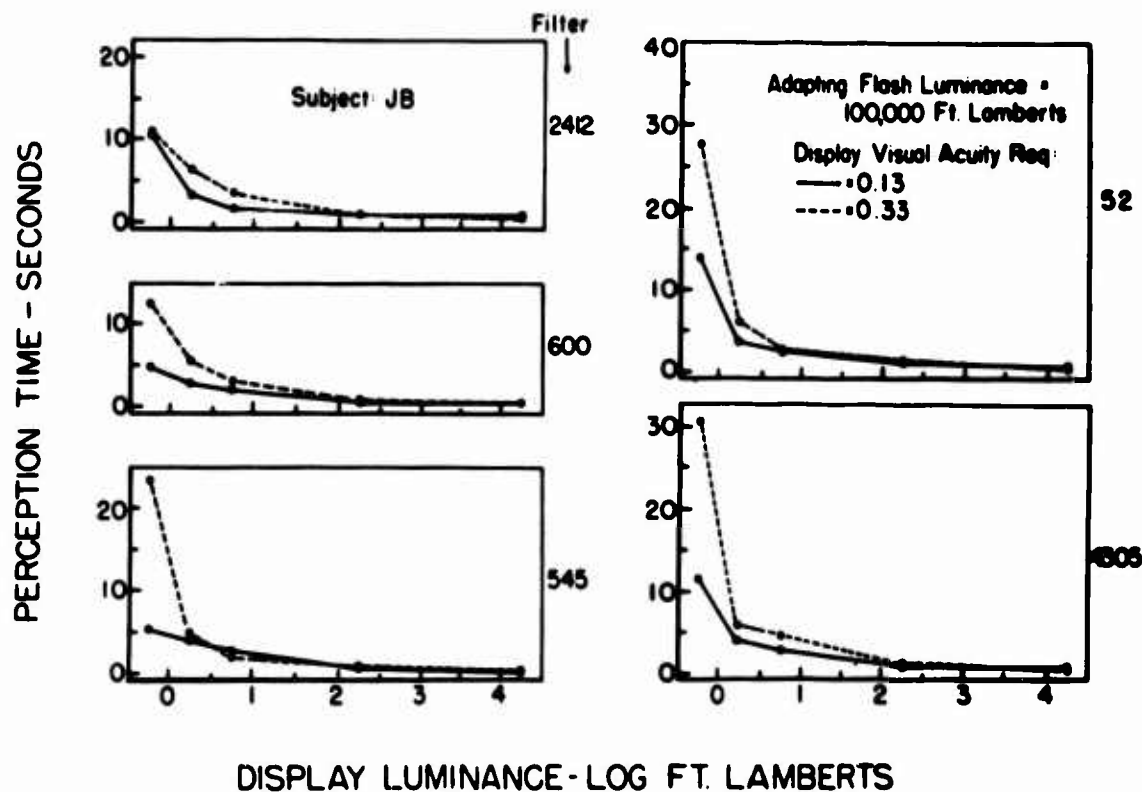
Fig.9   Time required for perception of the orientation of grating displays following
exposure to a 0.9 sec adapting flash of 100,000 ft-L. Color filters were in
front of the eyes, both during exposure to the flash and during viewing of
the grating.   The filters are Corning 2412-red, Bausch and Lomb 600-red
interference, Bausch and Lomb 545-green interference, Kodak 52-green, and
Corning 4305-blue.   Neutral filters were added to each of the color filters
to reduce total photometric transmittance to 1% (from Brown, 1959)

EFFECTS OF SIMULATED RETINAL BURNS ON
DETECTABILITY AND LEGIBILITY

by

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SUMMARY

Blind areas in the visual field of human subjects were simulated by
use of the after image of an intense light source. The subjects' ability
to perform a legibility task (reading digits) was greatly affected by
the size of the blinded area, and by whether it was located in the fovea
or the near periphery. Performance of a detectability (search) task
was also degraded when there was an experimental blind area in the
visual field, but the effects were smaller and related less closely to
the size and position of the area. Differences between subjects
were large.

EFFECTS OF SIMULATED RETINAL BURNS ON
DETECTABILITY AND LEGIBILITY,

V.D.Hopkin and T.C.D.Whiteside

INTRODUCTION

If excessive light falls on the retina it can give rise to a burn similar to the familiar 'eclipse burn'. This retinal injury is almost always free from pain, so that the principal effect is simply a blind area in the field of vision. Almost invariably such a burn would arise only where the image of an extremely bright source was formed on the retina. Thus, light from diffuse reflectors such as cloud or snow can in general be disregarded as a source of possible retinal burns, even when the illuminating light is from that most intense of all sources, a nuclear detonation. On the other hand, spectral reflections, particularly where they mirror the fireball, may give rise to a retinal burn. It is obvious that where the burn is produced by the image of such a fireball somewhere in the direct line of vision, then the size of that image will vary inversely with the distance of the detonation from the observer. At close ranges, where the fireball would subtend a big angle at the eye, there are clearly other more pressing problems than the visual effects being considered here.

When there is a blind area in the visual field, the interference with performance of a task such as flying an aircraft would be greatest when the flash was directly in the line of sight, for the blind area would then be directly over the fovea centralis. However, even when laboratory experiments are carried out with an after-image situated on the fovea, subjects usually find, when the flash subtends a small angle, that they can fairly easily 'look round the edges' of the after-image and see sufficiently well to read instruments by the unstimulated retinal areas close to the fovea. On this basis, since the probability of receiving a flash directly on the fovea is small, one might expect that the individual who sustained the retinal burn might under most conditions be able to see sufficiently well to maintain control of his aircraft. The time for which the aviator may be blind obviously has certain critical limits when considered in relation to his task. Thus, being unable to see for 15 seconds may be acceptable in high altitude flight, whilst in low altitude flight the maximum permissible blind period may be reduced to, for example, five seconds or less, depending on the nature of the terrain beneath the aircraft.

Although the question being considered is primarily that of permanent loss of vision, the conclusions reached apply equally to temporary loss of vision from a source insufficiently intense to produce permanent damage yet sufficiently bright to reduce visual sensitivity in part of the visual field for an appreciable time. The aim of the present investigation is therefore, to determine the relative differences in time required to read a digital counter whose position in the visual field is

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known, and secondly to search for an object. One would expect that the longest
times would be associated with flashes in the central visual field and that the time
taken would be related directly to the angle subtended by the blind area. Other
workers have produced experimental retinal lesions in animals and birds, but it was
felt that the use of human volunteers would give more immediately practical answers.

Since there was no necessity, or indeed intention, to damage the eyes of the
subjects, the 'blind' area was produced by the after-image of a photographic flash
bulb discharged in various parts of the subjects' field of view, luminance of the
test being of course, adjusted so that the test could not be seen through the after-
image itself, which thus effectively constituted a blind area on the retina.

Although there is considerable literature on the effects of flash, much of it is
concentrated on detailed relationships between size, duration, and brightness of the
flash on the one hand, and recovery time according to various criteria on the other.
Most investigators have been concerned with effects on acuity and have measured
recovery in the fovea. Kinney and Connors[6] (1965) noted that the information
available on this subject is limited and that experimental effort has concentrated
on the following related topics:

1. The course of foveal dark adaptation and the effect on it of brief light
   exposures.

2. Atomic blast studies of the effect on acuity of brief intense flashes.

3. Foveal acuity studies after complete dark adaptation.

4. The effect of brief flashes on peripheral sensitivity and acuity.

In much of this work measurements were taken at the point when the present experiment
stopped; that is, the experimenters were interested in determining when the subjects
could see through the after-image of the flash, whereas the present experiment
concerns the ability to see round it while it remains impossible to see through it.
In their study on dark adaptation following a flash in the fovea, Kinney and Connors[6]
(1965) found that the times necessary to readapt to the previously determined acuity
threshold varied systematically with the intensity and duration of exposure, and that
the product of intensity and time gave a constant effect.

Periods of time to recover were also measured by Severin[8] (1961). The primary
purpose of his experiment was to evaluate the Meyer-Schwickerath-Zeiss light
coagulator as a tool for investigating flash blindness. He was also concerned to
establish if the visual effects of dazzle are consistent enough to be studied by
experiment, and concluded that they are. His use of only 4 subjects introduced the
problems of the number of subjects which should be used in experiments on this topic
and the population from which they should be drawn. Hill and Chisum[5] (1965) remarked
that the noxious nature of the stimulus made the applicability and significance of
data from a large number of observers questionable. Their findings with a group of 4
highly motivated subjects were not repeated with a group of 101 less highly
motivated observers. They argued that anything short of full co-operation from the
subjects could lead to spurious results. This is not an academic issue, because the
practical consequences are important. They found that in sophisticated subjects an
eye patch was an effective protection against flash blindness; in less sophisticated
subjects it was not.

One of the origins for this concern with individual differences was the experiment by Severin, Newton and Culver[9] (1962) whose subjects were 15 volunteers from the USAF School of Aerospace Medicine. They found highly significant differences between subjects for which they could suggest no explanation. These differences were large enough to warrant the suggestion that predictions of the operational consequences of flash exposure might have to be made on an individual basis, since the variability between people would render any general prediction highly unreliable.

An experiment by Metcalf and Horn[7] (1958), in which all the flashes were presented for the same duration of 0.1 sec, showed a linear relationship between the log flash luminance and the recovery time to detect a stimulus. Whiteside's[10] (1960) findings supported this. Fry and Miller[4] (1964) held the luminance of the flash constant and varied its duration, and concluded that the data from their own experiment and from that of Metcalf and Horn[7] confirmed a reciprocal relationship between intensity and duration of flash. Although the data supporting these relationships are derived from several experiments, each with only a few subjects, their cumulative evidence is strong. An earlier experiment by Chisum and Hill[3] (1961) had suggested that flash duration might be a relatively unimportant factor, although they confirmed that recovery time was a positively accelerated function of total energy. In their experiment a 60-fold decrease in flash duration halved recovery time. The flash durations were brief - 9 milliseconds and 165 microseconds. The main purpose of their experiment was to study if the effects of a flash could be ameliorated by an automatic increase in the illumination of the displays within the cockpit as soon as possible after a flash. Brown[1] (1964) has surveyed experiments on flash blindness and attempted to quantify the relationships among some of the most important variables. His work established that recovery from flash blindness is not simple but that for a wide range of conditions it can be represented in quite a simple form. Throughout all this work, however, the experimenters have been influenced by the nature of the stimulus to reduce as far as possible the number of subjects taking part and the number of flash presentations. Therefore, although the large differences between subjects are known, their full extent and implications are far less certain. Brown[2] (1965) has provided a useful survey of flash blindness and of the relevant literature.

The emphasis on the recovery time in the literature on flash blindness has perhaps led to the lack of work on how the effects of blindness can be circumvented while the blindness is still present. Attempts to overcome the effects of blindness have centred on factors such as changing automatically the lighting of the most essential instruments in the cockpit, or providing an eye patch so that one eye remains relatively unaffected. The ability of the operator to see round the blind area has apparently not been tested and this paper reports an attempt to study that aspect of the problem.

APPARATUS

The general experimental situation is illustrated in Figures 1 and 2. These show a metal plate with nine apertures, each subtending an angle of 5° at the eye. By masking all but one of these at a time, each flash was presented at a previously determined angle to the line of sight. Two similar plates contained apertures subtending an angle of $\frac{1}{2}^O$ and 2^O respectively, with the centres of the apertures at

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the same angles from the line of sight (Fig. 2). The fixation light, seen by partial reflection, was so positioned that the distance of the visual image was the same as that of the masking plate, thus eliminating inaccuracies in fixation due to head positioning and movement.

The arrangement of the apertures is seen in Figure 2. A preliminary experiment revealed that the results of flashes in the near periphery and in the far periphery would be similar. Therefore during the experiments described here no flash was presented in the far periphery, except as an initial demonstration of the procedure. With this apparatus two separate experiments were conducted, the first on legibility and the second on detectability.

EXPERIMENT 1

Procedure

In the first experiment the task was to read the last two digits in the counter illustrated in Figure 2. Subjects used alternate eyes for consecutive flashes. They covered with one had the eye they were not using and held in the other a neutral density filter with a 70% reduction in transmission, to reduce the overall intensity of the flash stimulus. The counter with the digits was pivoted to the side so that it was not visible. The subject looked at the fixation light and was instructed to try not to blink. All lights were extinguished except for the fixation light and a 5 second count down given. At zero the experimenter pressed a button which both triggered the flash bulb and started the counter, which then changed once per second. As the light was flashed the counter was pivoted for the subject to read it. He was familiar with the position of the display, and preliminary experiments showed that no special advantage was gained by instructing him to hold the counter and thus obtain positional knowledge by hand-eye co-ordination. The counter was lit to the level of 3.4 cd/m^2 by its own light source. The subject was instructed, as soon as the flash was over, to continue to cover the eye he was not using, to remove the neutral density filter, and to look at the digital counter and read out the last two digits as soon as he could see them, and continue to read them out as they changed each second. Any change in the sequence of reading denoted an initial misreading. The number first read gave the time in seconds from the presentation of the flash, since the experimenter had noted the reading on the digits before the flash was presented. The pause between successive flash presentations averaged about 1½ minutes with a variation of only a few seconds. After the subject had read the digits, a small indirect light was switched on, sufficient to allow the experimenter to record the subject's response, to reset the counter and to put in the correct bulb and plate for the next presentation.

In this experiment 11 flashes were presented. These were the 4° and 5° flashes at all 4 positions in the near periphery, together with the 4°, 2^O and 5° flashes at the central position. The order of presentation was randomised with a different random sequence for each subject. The only non-random feature was that the central flashes were always the 3rd, 6th and 9th of the 11 presentations. Twelve subjects participated. All were drawn from the scientific staff of the laboratory and their co-operation could be depended on.

Results

Results from the central and peripheral flashes were analysed separately, the measure being mean response times from the presentation of the flash to the first correct reading of the digits. The mean time for the small flashes was 1.75 sec and for the large flashes 3.06 sec, giving a mean response time for all peripheral flashes of 2.41 sec. The difference between the small and large flashes is statistically significant at the 0.1% level. That there was no significant learning effect was demonstrated by comparing the first and second halves of the experiment which produced almost identical mean response times.

The mean response times to the central stimuli were 4.75 sec for the 4° flash, 20.5 sec for the 2° flash and 26.75 sec for the 5° flash. These last two means include a few instances when the subject found that the blinded area was so large that it was impossible for him to read the digits while it existed, and he was able to perform the task only when the after-image had decayed sufficiently for him to see through it. These instances were distinguished from those where the subject was successful in reading the digits 'round the edge'. After each central flash the subject was asked if he had succeeded in seeing round the edge, or had been forced to wait until he could see through the after-image. Failure to see round the edge meant that the task was impossible.

The difference in mean times between the largest peripheral light (3.06 sec) and the smallest central one (4.75 sec) is significant at the 1% level. An examination of the data from each of the 4 peripheral positions indicated that position had no significant influence on results and that the finding of longer reading times with the larger peripheral flashes was consistent for all flash positions. There were large and highly significant subject differences in performance of this task, particularly in the response times to a central flash. Whereas one subject successfully read the digits within 4 seconds after the largest central flash, others completely failed to do so. Eventually, after some 40 seconds, they saw through the after-image. These differences between subjects seem to be partly a function of the subject's peripheral acuity and partly of his ability to find the best technique for reading round the edge of the blinded area. An analysis of variance showed that both the size of the stimulus and the differences between subjects were highly significant but that they did not interact significantly.

EXPERIMENT 2

Procedure

In this experiment on detectability, the subject's task after the presentation of the flash was to scan round the room to find which one of 8 small lights was on. For this search task the luminance of the lights was set to about 13 cd/m^2, and each light subtended an angle of 10 mins of arc from the eye. This luminance had been selected so that the light would not be visible through the after image until some 40 secs after the flash. The room was otherwise black. The 8 lights were grouped in 2 sets of 4. Those in one set were placed at random at 30° from the fixation point and those in the other set at 60° from the fixation point, no two being close together.

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For the sake of comfort, the subject, as in the first experiment, received the flash
through the neutral density filter and after a 5 second count down. As the flash
was triggered the search task was switched on. The delay until the subject responded
by saying 'yes' was timed by a stop watch. He pointed to the light he had detected
and continued to do so until his answer had been verified. No errors were made.
The flashes presented were exactly the same as in the experiment on legibility, except
that the 2° central flash was omitted. A control run, in which all 8 search tasks
were presented in turn with no flash, preceded the experiment. During this control
experiment the subject covered both eyes during the count down and uncovered one eye
at zero. The search task was switched on during the count down. Each test light was
presented in a different random order for each subject, with the 8 peripheral flashes;
2 of the 8 test lights were selected for the central flashes for each subject. It was
intended to use the same 12 subjects in both experiments, but one was not available
when this second experiment was performed and a replacement subject was used.

Results

The mean time on the control runs (1.91 secs) was significantly shorter than when
a flash was presented (3.11 secs). The mean time taken for the search task was not
significantly different for a central flash (3.06 secs) than for a peripheral one
(3.125 secs). There were large individual differences between the subjects in their
mean response times, although the range in these times was much smaller in this
detectability experiment (2.15 secs to 4.70 secs) than it had been in the legibility
task (3.73 secs to 10.27 secs). The longest time taken to find a light was 7 seconds.
One aspect in which the subjects differed was in the way their responses were
affected by the size of the flash. Thus, the factor of size itself had a
considerable effect, but subjects were not uniform in their responses to it. This
was revealed by a significant interaction between subjects and size in an analysis of
variance.

DISCUSSION

The presence of an area of blindness affected the performance of these two tasks
in different ways. In the legibility task, which depends so much on foveal vision,
the presence of a large blind central area naturally had a very marked effect. There
was considerable variation in the ability of subjects to compensate for this effect,
and indeed some subjects were quite unable to read round the edges of the larger
after-images. Relevant factors here are consequently the subject's ability to find
the technique for overcoming the loss of central vision and his persistence in
searching for such a technique. Differences between subjects are certainly
contributed to by the acuity of their vision a few degrees from the fovea, although
there were no marked uncorrected refractive errors in any of the subjects tested.
Again, in regard to differences between subjects, it must be considered that the
motivation was probably not uniform and that some subjects were affected more than
others by a startle effect. Before each experiment, efforts were always made to
familiarise each subject with the procedures and with the experience of the flash,
but none the less the subject still had to contend with an inclination to blink and
had to remember not to uncover the eye he was not using.

In spite of these potential disadvantages, the experiment clearly showed the effect of the size of the blind area and its retinal position in relation to this particular legibility task. The experiment on searching for, and detecting lights revealed that these factors are much less important in this task. The light was often successfully detected in the far periphery, but subjects sometimes found it disconcerting when, having successfully detected a stimulus by means of peripheral vision, they were unable to confirm its presence with central vision because of the blinded area. Nevertheless, this did not lead them to doubt the peripheral observations and these detections were in fact always correct. The shorter times for the control search task illustrate that a blinded area does have an adverse effect on the performance of this task, but that the particular area of the retina which is blinded is much less critical.

These two tasks were chosen as representative (in a greatly simplified form) of the task of flying an aircraft on instruments. The results do, however, indicate that all but the largest flashes have little effect upon the performance of these two tasks. The greatest effect is that caused by a foveally centred blind area, but even then, the ability in using off-centre vision to detect and to read suggests that in all but the large blind areas, the individual may well compensate adequately. The differences in ability to compensate, suggest that the use of off-centre vision is a skill in which performance can be improved by simulation and training.

The relevance of this investigation to the flying task will be studied at a later stage by using a similar technique in conjunction with a flight simulator.

ACKNOWLEDGMENT

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Figure 1

R = Reflector
C = Counter
L = Fixation Light
F = Flash Bulb
B = Baffle Plate

Banked Switch

24 V.

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R = Reflector
C = Counter
L = Fixation Light
B = Baffle Plate
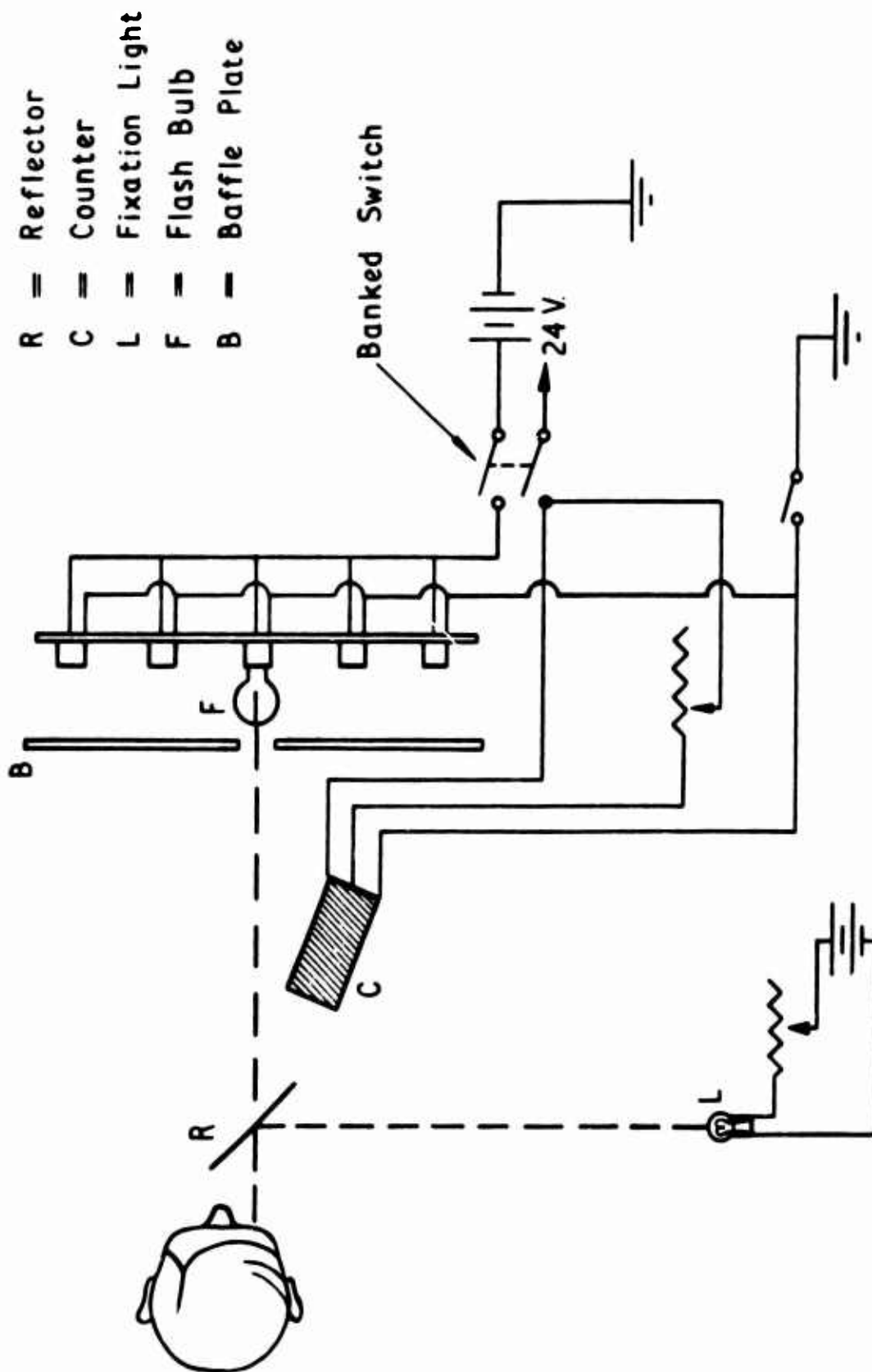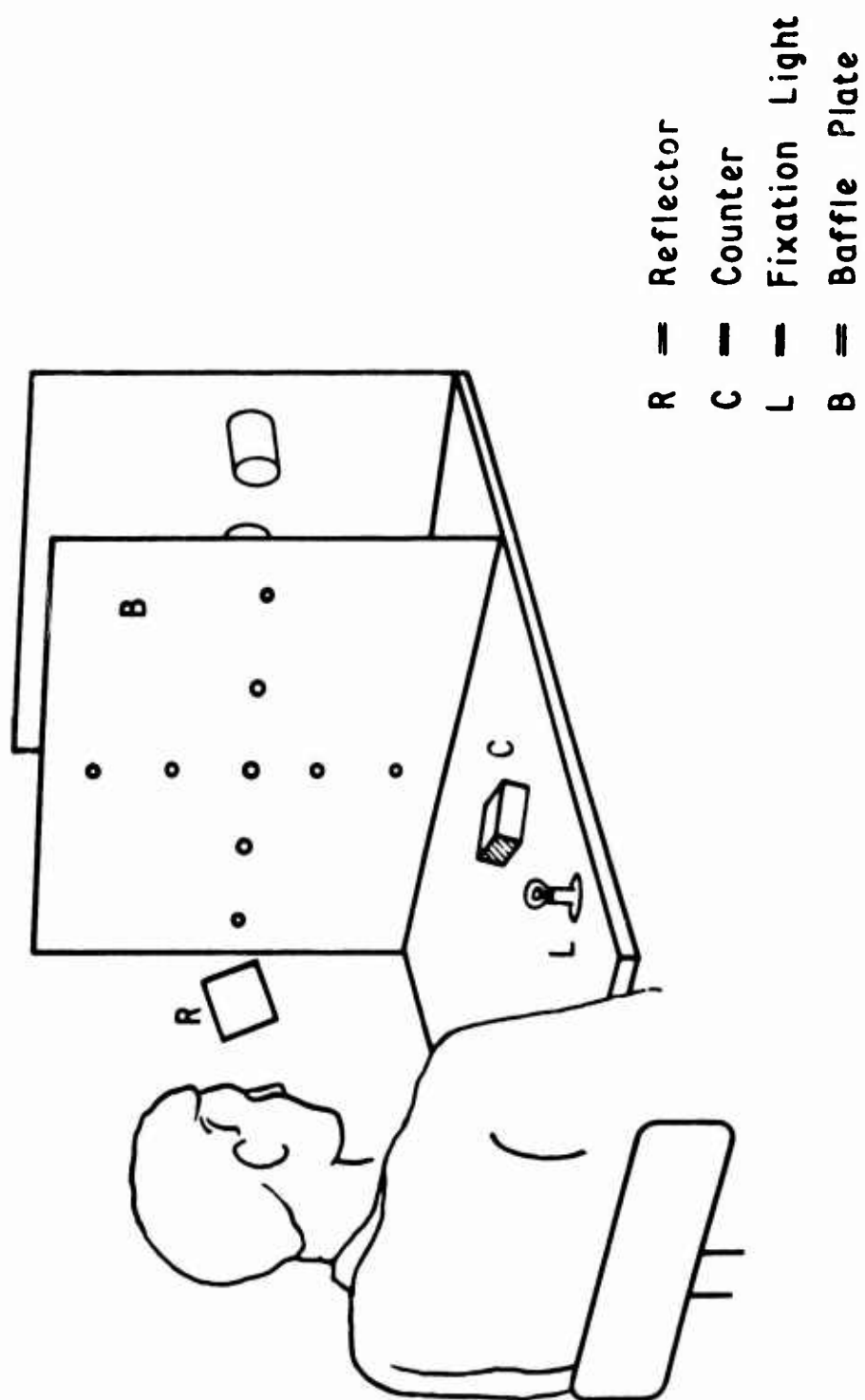
Figure 2

PRESERVING VISION DESPITE EXPOSURE
TO HIGH INTENSITY LIGHT

by

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SUMMARY

Preliminary experiments have suggested that shading of areas of the retina, particularly the macular region, can give considerable protection from glare. Engineering of the task that must be performed and then design of shading of part of the retina may, in combination, allow continuous efficient performance both before and after exposure to bright light.

PRESERVING VISION DESPITE EXPOSURE
TO HIGH INTENSITY LIGHT

Clement McCulloch and John R. Elder

INTRODUCTION

Photostress, whether it is severe as flash blindness, or moderate as from glare on the highway at night, is only of significance when considered with respect to the job that must be done. There is advantage in analysing the work a man must do before considering the glare to which he will be exposed. Modifications of the task can decrease the importance of unavoidable glare. Protection can be arranged to preserve a specific performance.

There must be an element of shock or hysteria in flash blindness. A hysterical response to ordinary glare seems to be common, as witnessed by the fad for sunglasses and in the habits of automobile drivers who "freeze" in the face of bright headlights. One would wonder if a percentage of the value of the contrivances being discussed to protect against bright light is not psychic – the assurance of a positive response to a threat. Modification of the work to be done, training of the man to do it despite severe photostress, may be of psychic as well as physiologic value.

THE TASK ASSIGNED TO THE SUBJECT

From a practical or a clinical point of view what we do visually may be classified into five groups:

1. fine discrimination, such as reading fine print,
2. follow tasks, such as following print across a line or following the flight of an aircraft,
3. search tasks, such as scanning for an aircraft in the sky, searching for any small object,
4. colour vision,
5. night vision.

For each of these groups the visual apparatus is used differently. The relative importance of these five functions varies from task to task and protective measures can be tailored to preserve certain functions for a certain task. Fine discrimination requires macular vision. Follow tasks require for small objects, both the macula and some surrounding retina. Search for small objects requires only the macula; for large objects the use of the mid-peripheral retina may be sufficient. Colour vision depends principally on the macula, night vision only on the mid-peripheral retina.

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To bring together the general considerations, using the aviator as an example, we should first define his essential duties during two minutes following explosion of a bomb. Let us say it is sufficient that he look at one dial in his cockpit and give up vision outside the aircraft. On that basis the macula must be preserved and the rest of the retina may be sacrificed. Search for small objects is impossible, follow is difficult, night vision is gone but colour may be used. Our second consideration is to modify his visual task (the dial) to his advantage — larger numbers, greater brightness. Our third consideration is to protect the macula even if we lose all the rest of the retina.

Glare represents a complex situation that may be analyzed in a number of ways. One way is to break it down into components like a shopping list. This is not satisfactory because the components overlap. A second way is to establish relationships, indicating the interdependency of the factors involved. I have chosen a little of each, realizing there are deficiencies.

THE SOURCE OF GLARE

The physical properties of the glaring light may be listed as:

1. brightness
2. spectral distribution
3. duration
4. angular size.

It is reasonable to expect that increasing brightness is related to increasing glare. Also, there should be an upper limit or level of brightness where maximum glare is produced and beyond that level there should be no further decrement to vision. At extreme energy ranges a retinal burn and permanent loss of vision would occur. The literature confirms this view.

When considering flash blindness duration of exposure to the source of light can be limited to the time of the blink reflex, or 0.1 seconds.

The amount of loss of vision may be related to the angular size of the glaring light. If the source, such as the fireball of the atomic bomb, has a very high energy level, not only is maximum glare produced but permanent retinal damage occurs. The fireball can sufficiently illuminate sky and surrounding clouds that they act as a secondary source, producing maximum glare but no damage. This extended effect reminds one of snow blindness at an extreme level.

Excellent studies of the effect of varying these physical factors on the severity of glare are in the literature.

THE SUBJECT

There are certain variables in the subject, the recipient of the intense light, that may be factors modifying the loss of vision that can occur:

1. size of pupil,

2. state of retinal adaptation,

3. area of retina affected,

4. the structure and particulate matter of the mediae of the eye,

5. the internal reflectance from the posterior coats of the eye.

The amount of light entering the eye will be approximately proportional to the area of the entrance pupil. The state of retinal adaptation may have effect on the ability of the subject to recover after glare. The loss of vision from bright light falling on one area of retina, such as macula, may be different from that produced by bright light falling on another area, such as peripheral retina.

Variability in structure of the mediae of the eye from person to person may be of significance. In the young this may not be large, although the incidence of sub-clinical variations in structure of lens and vitreous has not been studied. Certainly vitreous fibrillae change and particulate matter increases with age and with disease. Similarly the variability of internal reflectance of the retina and choroid is not known. In a clinical sense it is recognized that there are albino, blond, brunette and negroid fundi and that reflectance between these groups is grossly dissimilar. Presumably the amount of both internal scatter and reflectance is a direct function of intensity and has a relationship to the spectral distribution of the incident light.

NERVOUS SITES OF GLARE

The actual location at which loss of vision is produced by intense glaring light may be multiple. Four locations can be suggested:

1. retinal receptors,

2. association cells in the retina, horizontal and amacrine,

3. external geniculate body,

4. vision cortex and neighbouring centres.

Whether it is possible that an intense stimulus by light may flood all of these nervous areas causing "glare" at all sites is not known. If a function decrement occurs at all locations the type and time relationships must be distinct for each site.

The amount of bleaching of the visual pigments in the retinal receptor cells could account for prolonged recovery times. The effect would be geographic – corresponding to the area of the retina involved. Area relationship and time relationships for loss of vision from glare should conform to the speed of regeneration of the retinal pigments. One would expect that the time relations for retinal and for central inhibition would be different.

In view of the extensive work in other countries on the physical nature of sources of glare and on the construction of mechanical and chemical protective devices, Canadian interest has been restricted to two aspects of the problem. The first is a

consideration of the effect of radiation from a glare source falling on only part of the whole extent of the retina. The second is an analysis of tasks that must be done by subjects and modifications of such tasks to shorten the period of incapacity after glare.

Exposure of only a part of the retina to intense light is of interest to the clinician. The production of an absolute or a relative scotoma is well known and its use is regularly employed in the treatment of children with squint. If an area of false projection is present in a squinting eye, leading to eccentric fixation, the area may be blinded by exposure to bright light and the macular area stimulated to try and teach the patient to use central fixation. With persistent training a child may be taught to transfer fixation from an eccentric area to the macula. The procedure is a demonstration of the differential washing out of one retinal area without affecting the surrounding vision.

Also, it is well recognized that the extent, degree and duration of localized retinal adaptation varies with disease. This has been extensively studied by Dr John Locke in Montreal. He has found that after illumination of part of the retina he can chart a scotoma corresponding to the area illuminated. The scotoma gradually shrinks in size and disappears. However, in certain diseases, such as edema neighbouring the disc, edema at the macula, or glaucoma, the rate of which the induced scotoma disappear is greatly slowed. Measurement of the rate of disappearance of the scotoma following glare can be helpful in assessing the pathologic changes that may be present.

METHOD

Exploratory experiments have been done to assess if a localized scotoma does occur when a limited area of retina is illuminated. The apparatus in Figure 1 was used. The light source was the light coagulator of Meyer-Schwickerath, modified externally with lenses and a shutter mechanism. This produced a circular patch of light on a mat white screen. The brightness of the circle of light at the corneal plane was 5,056 foot-lamberts and the background illumination 0.014 foot-candles. The object used to test recovery of vision was a 2 mm. white target on a dark background affixed to the screen; illumination was 0.014 foot-candles.

After an initial ten minute period of dark adaptation one eye was covered. The subject sat with his chin on a rest viewing a fixation point on the screen. A 100 mm. circular patch of light subtending 50° at the nodal point of the eye was displayed on the screen for 147 milliseconds. Using the exposed eye, the time until the patient could see the test object was recorded on a Crammer timer. Four to ten tests were conducted in each experiment on two subjects allowing five minute adaptation between the tests

Experiment A: The light flash was located on the screen 30° to the side of the visual axis. The time required to see the test object placed both in the area of exposure and in the corresponding un-exposed retina, 30° to the opposite side of the visual axis, was recorded.

Experiment B: The light flash on the screen was centred on the visual axis. The recovery time with the test object placed centrally was recorded.

Experiment C: A flash of light was delivered to the diffusion screen, centred on the axis of fixation but opaque discs were interposed on the screen at the fixation point. This procedure exposed the eye but shaded the central retina from the flash. Recovery times until the central test object was seen were recorded.

Experiment D: The light flash was located on the diffusion screen, positioned at various degrees of obliquity to the visual axis (Fig.2). The time to see the test object placed centrally was recorded.

RESULTS

Table A and Figure 3

Light flash 30° to the side of the visual axis. Recovery times to see the test object on the side corresponding to exposed retina and on the opposite side, to the nearest one-tenth second.

	Exposed Side (seconds)		Unexposed Side (seconds)	
	Subject 1	Subject 2	Subject 1	Subject 2
	N = 10	N = 10	N = 10	N = 10
$\dfrac{\Sigma N}{N}$	32.1	43.1	4.2	4.1
$\dfrac{\Sigma d}{N}$	2.3	1.3	0.7	0.4

Table B

Light flash centred on the visual axis. Recovery times to see the test object on the visual axis.

	Trial 1		Trial 2		Trial 3	
	Subject 1	Subject 2	Subject 1	Subject 2	Subject 1	Subject 2
	N = 4	N = 8	N = 2	N = 5	N = 4	N = 4
$\dfrac{\Sigma N}{N}$	41.9	66.8	29.5	27.7	18.7	25.7
$\dfrac{\Sigma d}{N}$	5.9	5.9	0.4	2.3	1.6	4.1

Table C and Figure 4

Light flash centred on the visual axis. Opaque disc placed to cover the central or fixation point. Recovery times to see the test object on the visual axis.

Area of Retina Shaded (degrees)	Averages of Two Tests A Subject (seconds)	
	Subject 1	Subject 2
3	23.0	23.8
5	19.8	17.6
10	8.6	8.4
15	5.9	6.3
20	5.0	6.0
25	3.ᵒ	4.0
30	3.1	3.5

Table D and Figure 5

Flash at various degrees of obliquity to the visual axis. Times until test object could be seen with central vision.

Obliquity of Flash (degrees)	Averages of Four Tests A Subject (seconds)	
	Subject 1	Subject 2
5	19.6	23.8
10	17.2	21.7
15	15.8	17.7
20	14.4	13.5
30	5.3	5.5
45	2.9	3.6

METHOD

A similar group of experiments were carried out in a like manner using almost the same technique but substituting the Goldmann-Weekers adaptometer for testing the recovery of macular vision. The light source, shutter mechanism and diffusion screen were the same as previously described and shown in Figure 1. The subject, with his chin on a rest, viewed a central fixation point on the diffusion screen with one eye covered. Immediately following the dazzling flash of light, the subject turned to the Goldmann-Weekers adaptometer. The time to locate the gap in the Landolt test target with the exposed eye was recorded. The test object had a constant illumination of 0.01 Lux.

Three experiments similar in design to the last three tests of the former group were performed using only one subject.

Experiment E: The light flash was centred on the visual axis. Recovery times were recorded.

Experiment F: The light flash was centred on the visual axis but various sized opaque discs were interposed on the screen at the fixation point and recovery times recorded.

Experiment G: The light flash was delivered at various angles of obliquity to the line of fixation and recovery times recorded.

RESULTS

Results are shown in Tables E, F, and G. Figures 6 and 7 are graphic representations of results obtained by the two different recovery test targets.

Table E

Central flash recovery times

Recovery Times (seconds)
N = 10

$$\frac{\Sigma N}{N} = 61.6 \qquad \frac{\Sigma d}{N} = 8.8$$

Table F and Figure 6

Light flash centred on fovea but various discs centrally placed, providing protection. Recovery times recorded.

Area of Retina Shaded (degrees)	No. of Tests	Mean Value (seconds)	$\frac{\Sigma d}{N}$
3	10	40.1	2.1
5	10	22.3	3.0
10	6	12.2	1.7
15	6	7.7	0.3
20	6	5.6	0.2
25	6	5.0	0.4
30	6	4.0	0.2

Table G and Figure 7

Oblique flashes of light at various angles to the visual axis and the mean recovery times for each angle.

Angle of Obliquity (degrees)	Mean Value of Six Tests (seconds)	$\frac{Zd}{N}$
5	39.2	3.9
10	30.9	1.9
15	25.2	3.3
20	23.8	2.3
30	11.6	1.4
45	4.9	0.6

CONCLUSIONS

Both with the largest central protecting disc and with the greatest obliquity of dazzling light that was used some degree of temporary loss of sight occurred.

Significant protection of central vision was also achieved when an area 5° to each side of fixation - 10° across - was shaded from the dazzling light.

Significant protection of central vision was also achieved when the dazzling light was eccentrically placed to clear the fixation point by 5°.

When the dazzling light was obliquely placed - before one side of the retina only - recovery of vision was slower on that side than on the unexposed side.

These results can only be considered applicable to light levels in the region of 5,000 foot lamberts; further investigation would be necessary to consider higher levels of brightness.

PROTECTIVE DEVICES

A number of schemes to protect against flash blindness have been described in the literature. These include low transmission filters and sophisticated shutters triggered by chemical or mechanical means. Of rather simple concept and low cost are various forms of cover. The simplest and cheapest is to close or cover one eye, opening after the exposure to glare is over. A second plan would be to cover or shade part of the visual field of each eye. For example, an aviator could have a large part of his visual field covered, protecting him from a bright source in the sky, and have his lower field unencumbered, giving him a free view into his cockpit. The shade need not be opaque, but could have low transmission. Another device could be a slit spectacle, such as eskimos use for snow blindness. This would give considerable protection, only when the source of glare was straight ahead would its full effect be developed. In general, shading devices allow only a limited field, the effectiveness corresponding inversely to the size of the field.

SHADING OF NON-CORRESPONDING VISUAL FIELDS

Some increase of field, without sacrificing protection, can be obtained by covering non-corresponding points of the two retinae. An example is spectacles constructed to shade the lateral half of the visual field of each eye (Fig.8). The objectives are to obtain a relatively large, unencumbered visual field, as good visual acuity is possible, a high likelihood of blocking the macular area from direct exposure to the source of glare and complete shading of a large proportion of the peripheral retina.

The geometry of such spectacles is shown in the accompanying diagram (Fig.9). The lateral half of each lens is shaded, the shading ending at the visual axis when the eyes are looking to infinity. Transmission in the shaded parts of the lenses is quite low, without being opaque; values in the region of 2% appear to be suitable.

The view through these glasses for different positions of gaze indicates the extent of field and the protection obtained by this method of shading. When looking to infinity the right eye will see approximately 45° medially and laterally up to a vertical line passing through the fixation axis. The separation between seeing and covered appears as a penumbra, its width governed by the size of the pupil. The left eye will see medially 45° and laterally up to a line running vertically through the visual axis. The field of vision obtained using the two eyes is 45° to either side and 45° upwards and downwards. There will be a central narrow area of binocular vision corresponding to the penumbra. If the source of glare lies to the right, the right macular region will be spared; if to the left, the left macular region will be spared. If the source of glare is extensive, such as a brightly illuminated sky, one half of the retina in either eye will be spared, up to the region of the macula. The possibility of a point source of glare directly illuminating both maculae would be extremely small, as the fixation axis, the fit of the glasses and the source would all have to be in line. In any other position at least one macula would be protected. After glare, to uncover the shaded retina, it is only necessary to turn the head.

When the subject turns his eyes 22½° to the left, slightly different relationships occur (Fig.10). The right eye has an oval field, having a vertical lateral boundary and a curved medial boundary. Fixation, corresponding to the macula, is approximately in the centre of this field. The visual field of the left eye has a vertical, lateral boundary, 22½° medial to fixation and a curved medial boundary approximately 55° medial to the fixation axis. The macula is shaded by opaque glass. A source of glare lying to the left would affect the central retina of the right eye but the left eye would be protected. A bright source to the right would be shaded from the right eye. A similar analysis can be made for eyes turned to the right.

If the eyes are converged to an object at 33 cm. distance, the visual fields shown in the accompanying figure will be obtained (Fig.11). The lateral border of the visual field of the right eye will be a vertical line 6° lateral to the fixation point. The visual field of the left eye will be similar. The joint visual field of the two eyes is shown. It consists of a vertical, central band of binocular vision, 12° in width. To either side of this the field extends approximately 39° as monocular vision, the field ending in a curved border.

At no time will both maculae be exposed to a distant point source of glare. Both maculae will be protected from a source straight ahead since they are tucked behind

the opaque glass. A source to either side could illuminate only one macula at a time. The combined field of exposure to a distant source is shown in the accompanying figure (Fig. 11). There is a central area extending 6° where macular protection is binocular. To each side of this 39° of field in which there may be monocular exposure.

Such partially shaded glasses give a person continuous one-eyed cover and allow him to look in the distance in all directions with his field little reduced. At the same time his near vision is stereoscopic and he has protection from a distant source of glare. If his job involves white material, such as paper, this may act as a secondary source of glare, involving both maculae and 6° lateral to the maculae.

ENGINEERING OF THE TASK

To handle secondary near sources of glare engineering of the task should be considered. In this regard, three variables can be mentioned:

(a) to increase the illumination upon the task,

(b) enlarge the objects involved in the task, such as type,

(c) reduce the reflextance so that when the objects are brightly illuminated, none shall be sufficiently bright to act as a secondary source of glare.

White printing on black paper is a good example. This is occasionally used by institutes for the blind as an improved form of type for individuals with low acuity due to opacities of the cornea, in the lens or diffuse haze in the vitreous. These patients are bothered by scatter due to opacities in the media; white print on black paper decreases the scatter and allows better visual acuity. In a normally sighted person, such printing greatly reduces glare from a bright source of light.

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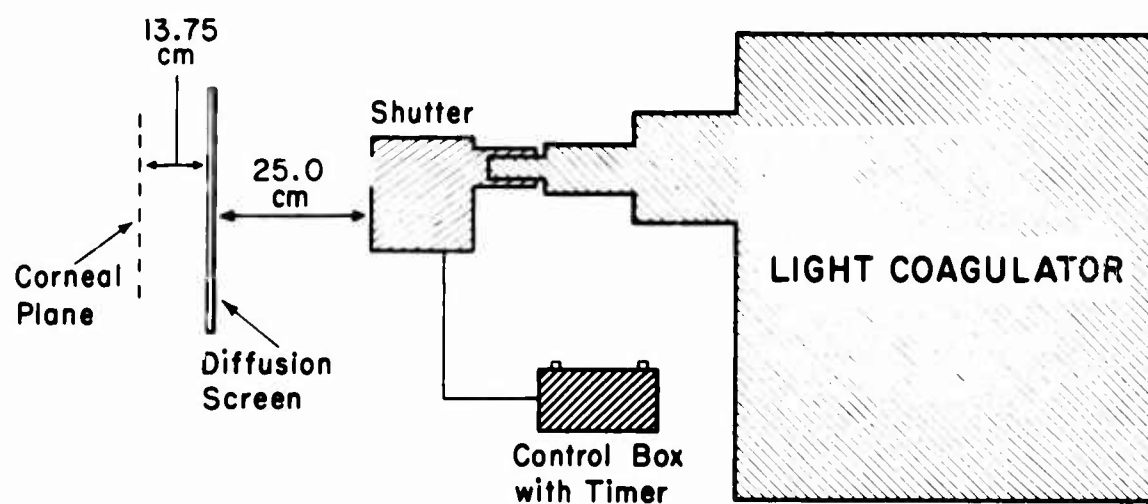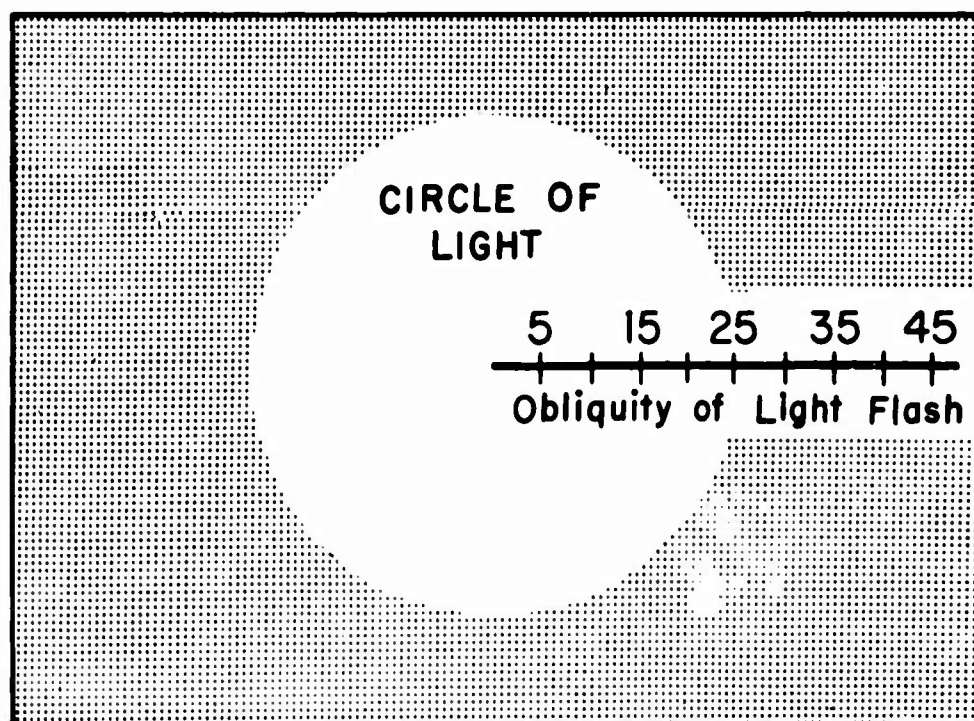   Report No.1075, 1 March 1960.

Fig.1   Side view of apparatus
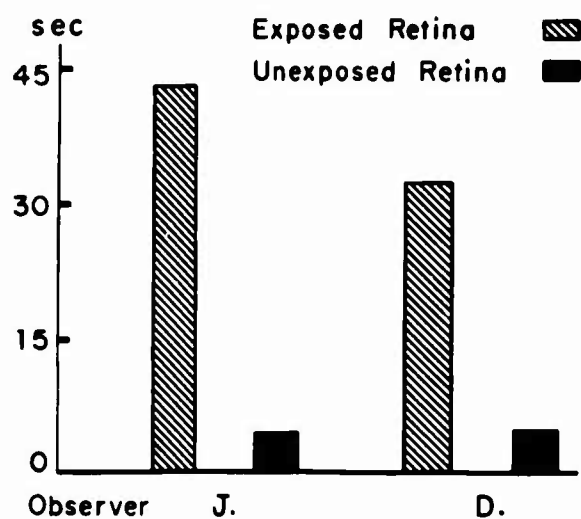

Fig.2   Fixation points on diffusion screen
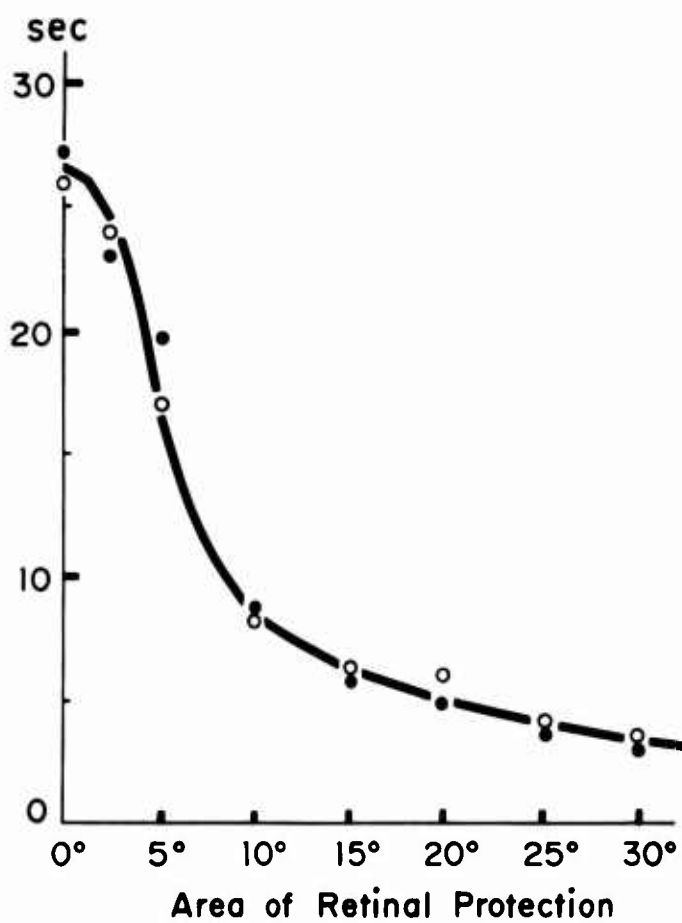
Fig. 3   Oblique flash recovery times

Fig. 4   Mean visual recovery times following light flash

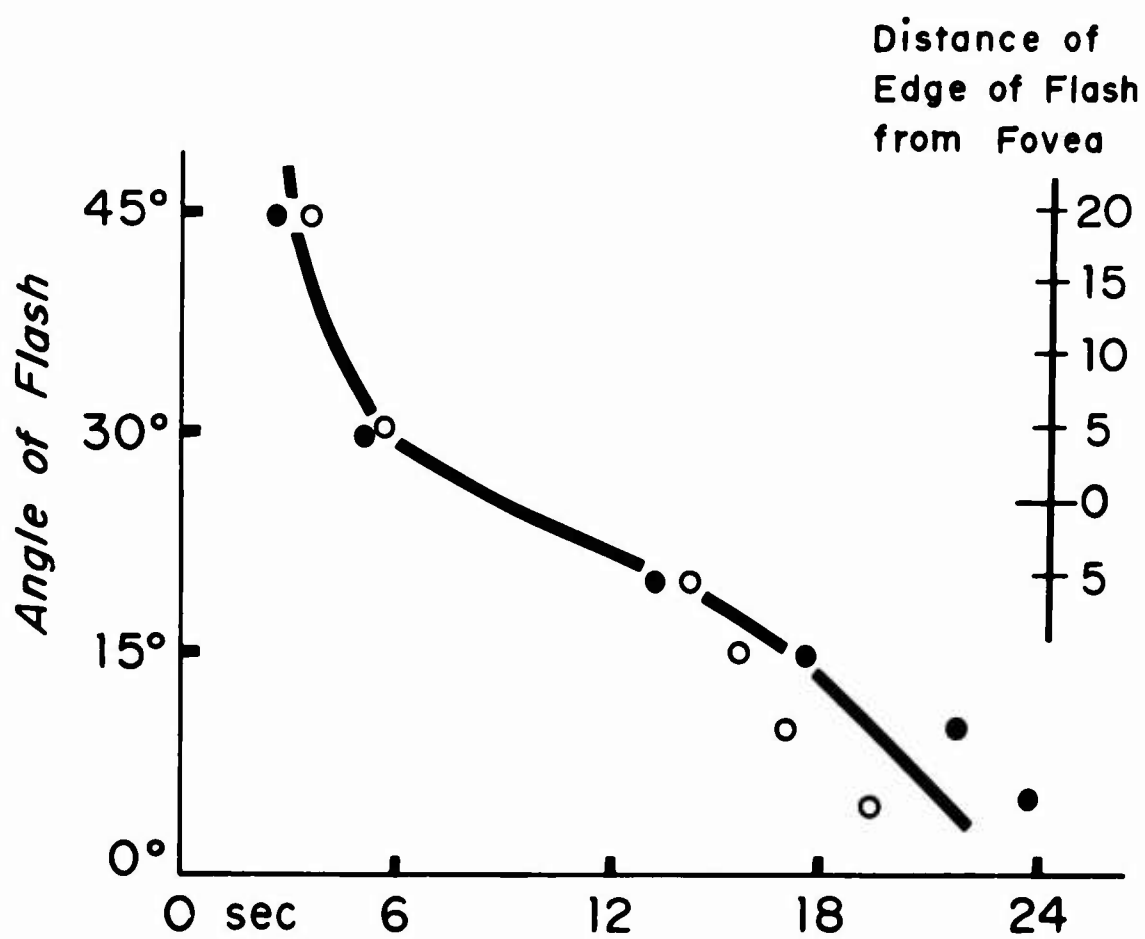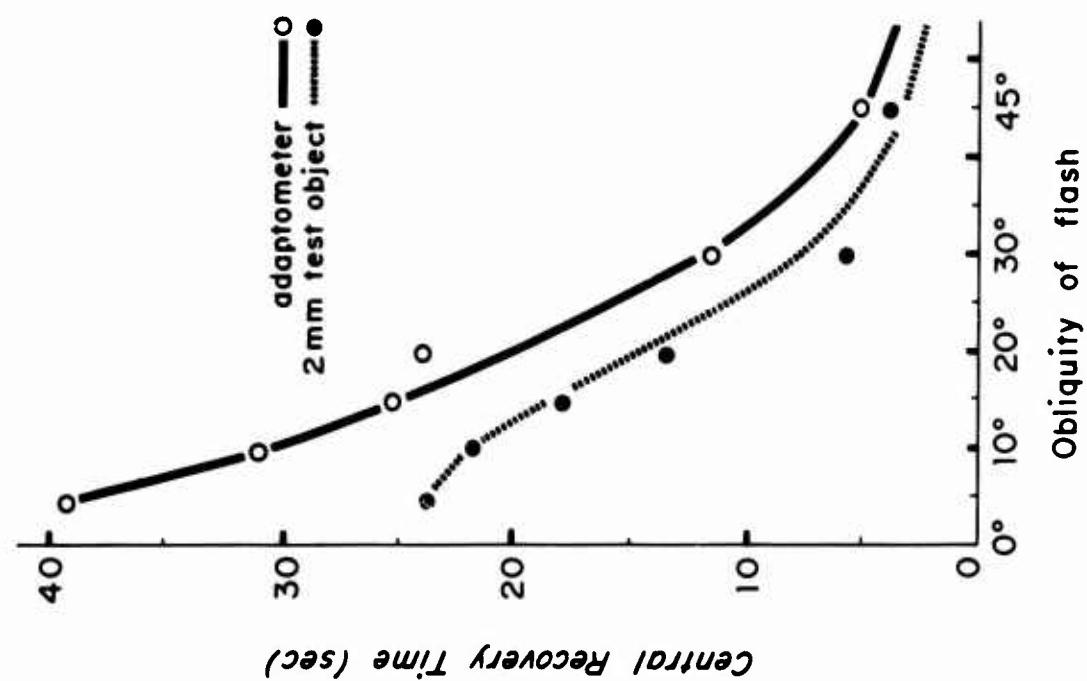Fig. 5   Mean recovery times for increasing obliquity of flash

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Figure 7

Central Recovery Time (sec)

Obliquity of flash

adaptometer ○
2mm test object ● ·······

Figure 6

Central Recovery Time (sec)

Area of Retinal Protection

adaptometer ○
2mm test object ● ·······
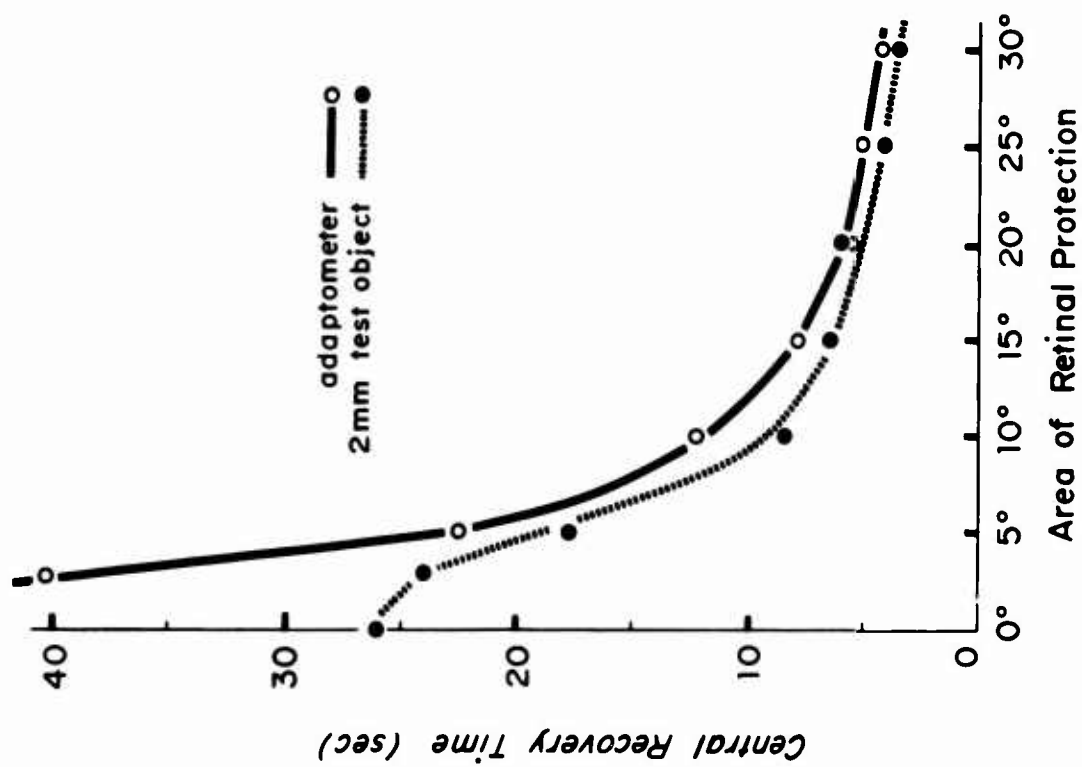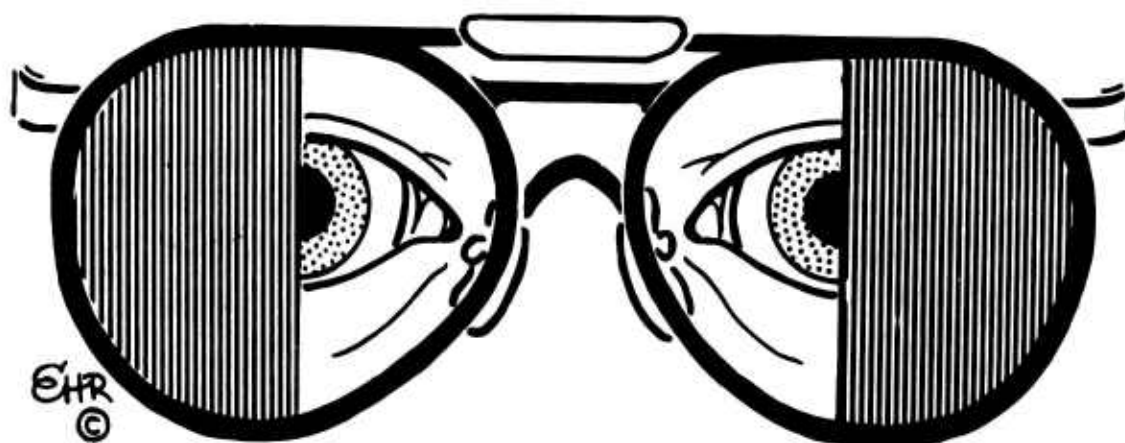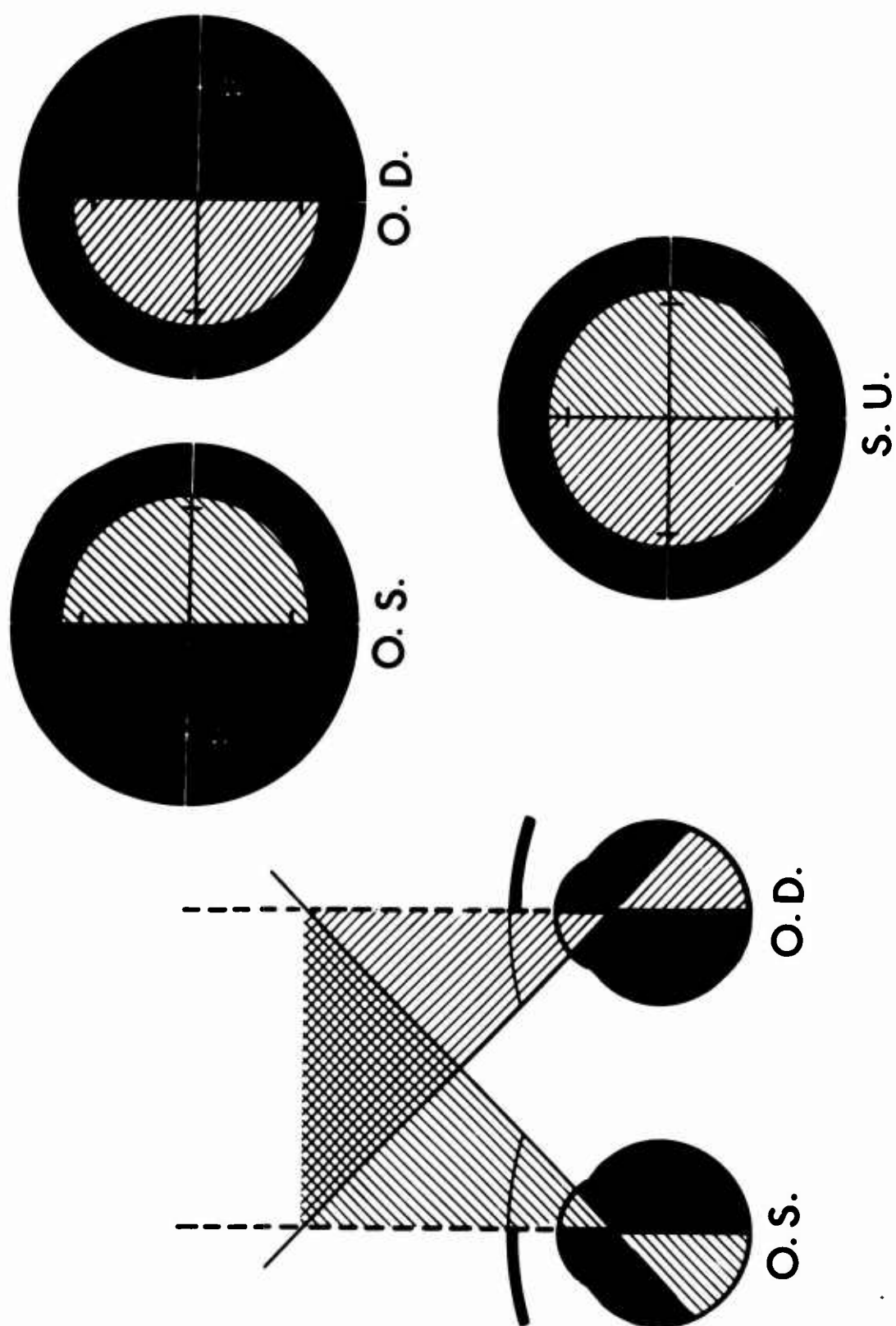
Fig. 8   Spectacles with lateral half of each lens shaded

Fig. 9   The geometry of spectacles of Figure 8
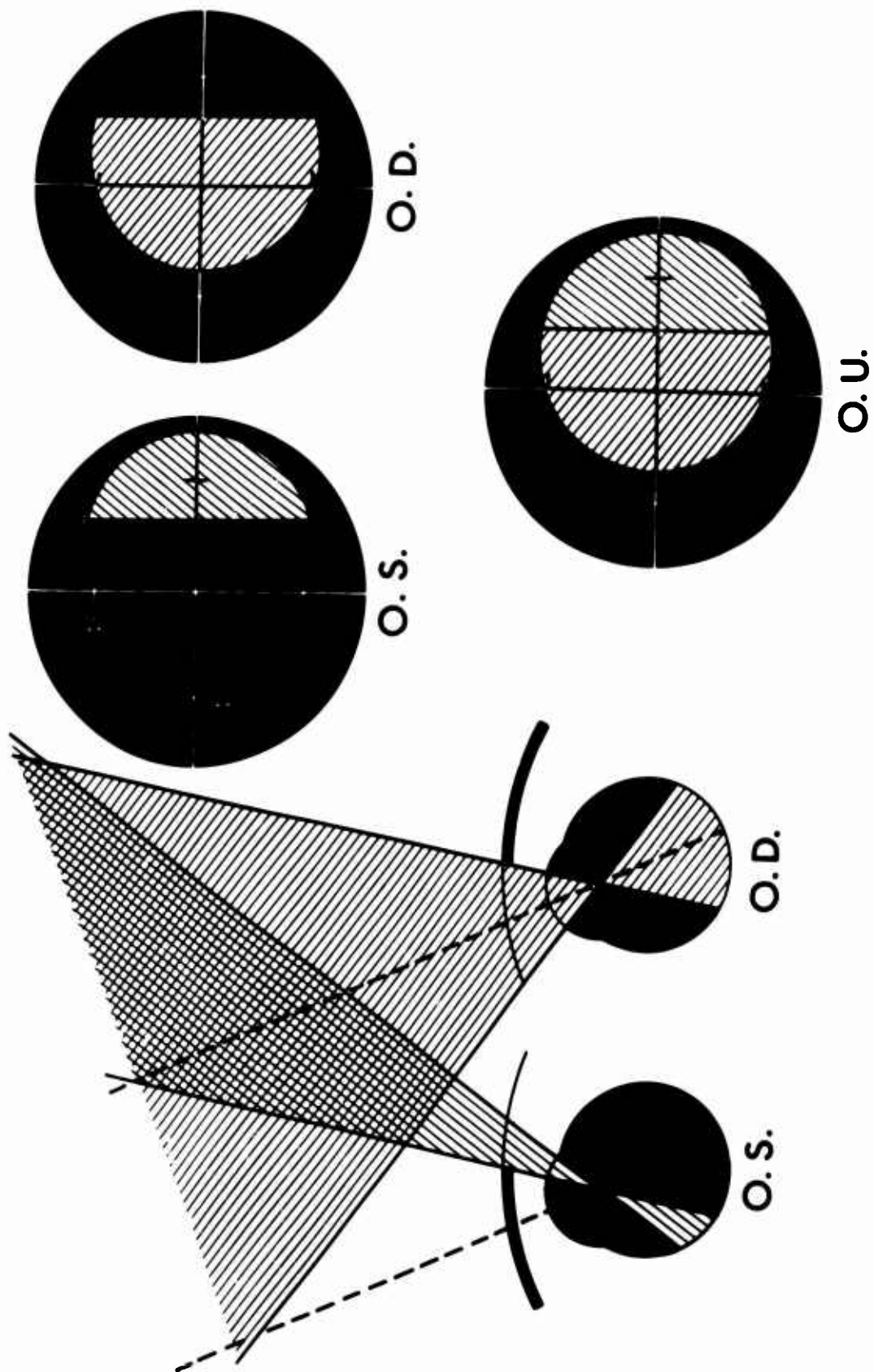
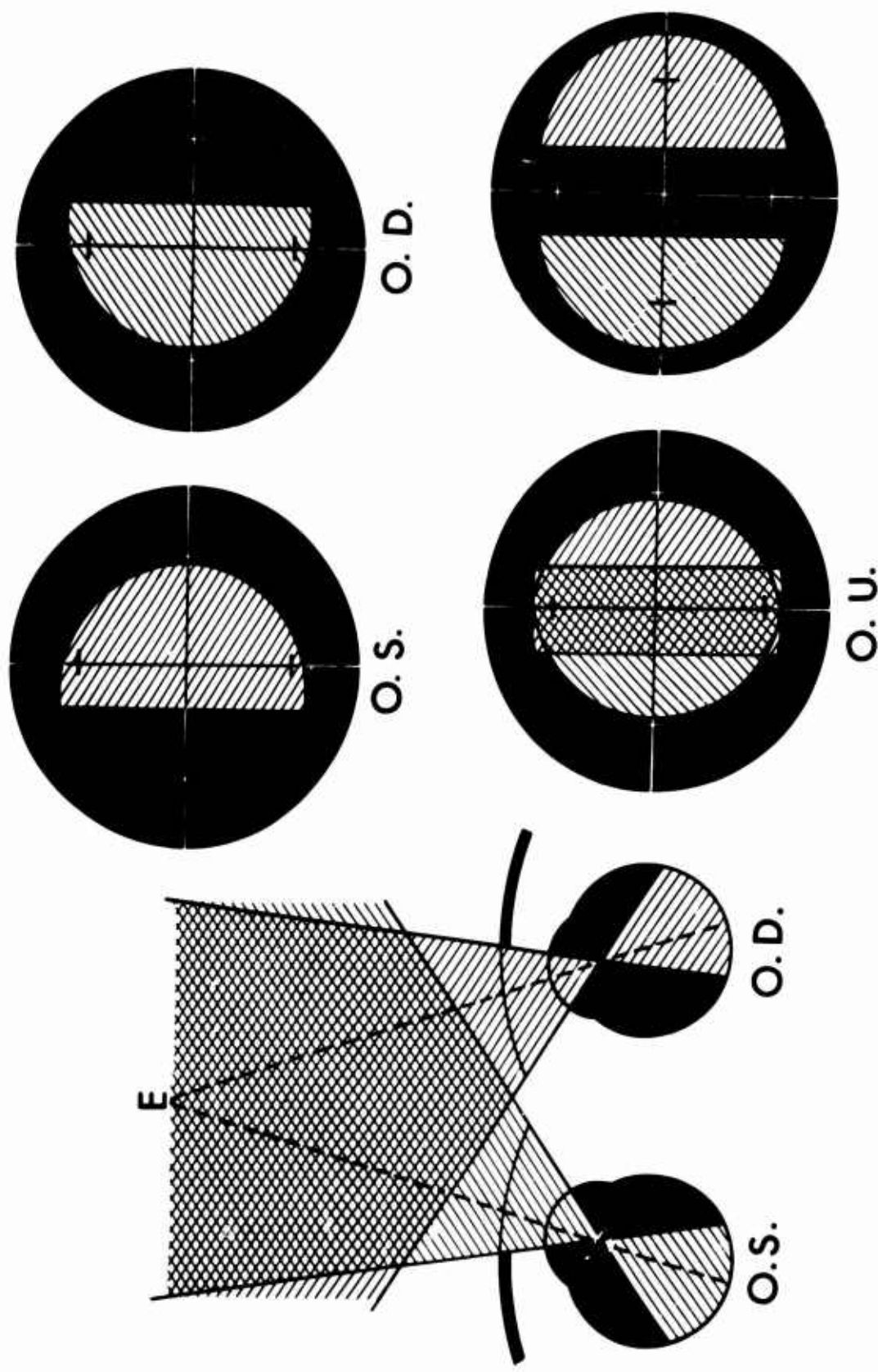Fig. 10   Geometry with eyes turned 22½° to the left

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Fig.11 Retinal illumination from infinity

THE SUCCESS OF US NAVY EQUIPMENT DEVELOPMENT PROGRAMS
IN MEETING THE FLASH BLINDNESS PROBLEM

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SUMMARY

The Navy program for protecting against flash blindness has pursued
a number of avenues. A low-tranmission visor system has been developed,
which appears to be entirely adequate for day operations. A concerted
program has been maintained for the development of a satisfactory active
device which will provide protection at night. Present results point
toward a successful conclusion for these efforts. And f'nally, a
comprehensive training program has been established so that pilots will
understand the flash blindness problem and will use correctly the
protective equipment being issued to them.

THE SUCCESS OF US NAVY EQUIPMENT DEVELOPMENT PROGRAMS IN MEETING THE FLASH BLINDNESS PROBLEM

James F.Parker, Jr. and Roland A.Bosee

INTRODUCTION

The efforts of the US Navy to combat the flash blindness problem now have spanned a full decade. This seems, then, an appropriate time to review the major features of this program to assess the progress which has been made, and to list some of the hurdles which are yet to be surmounted. In 1956, some eleven years after the first nuclear detonation, military personnel were just beginning to become concerned with the visible energy released by nuclear bursts. This was just one year after Byrnes published his well-known analysis of the chorioretinal burn problem and four years after Whiteside's paper on the dazzle effect from nuclear bursts at night. In historical perspective, it may seem unusual that there should have been such a delay in appreciation of a problem area of this consequence. However, it seems that until this time interest had been focused on the truly awesome effects of blast, shock, thermal radiation, and ionizing radiation from nuclear weapons. It simply took a period of time, approximately a decade, for attention to turn to the light energy which also is released.

INITIAL DEVELOPMENT EFFORTS

Initial efforts of the Navy were directed toward fixed-density visors which, it was hoped, would attenuate the light to an extent that would prevent retinal burns and reduce the severity of flash blindness. In 1958, general-purpose, light-restrictive filter goggles, known as LRFG-58, were issued. Figure 1 shows a photograph of these goggles. The goggles were constructed of a red plastic material with a photometric transmission of one percent. It was hoped that these goggles would allow a pilot to see well enough to fly during daylight by visual contact, and at night by instruments, when the instruments were floodlighted. In spite of the obvious protective benefit of these goggles, they are not being used by the Navy at this time. Primary reasons are excessive visual fatigue, limited peripheral vision, and an apparent insufficient transmission of light.

A second early effort was aimed primarily at providing protection from the thermal effects of the weapon, rather than at protecting against flash blindness. Figure 2 shows a cockpit enclosure designed to be closed by the pilot, thereby protecting him from thermal effects. In later aircraft, this protective hood, which is still under development, will close automatically, in less than one-half second, when energy from a burst is detected. Thus some measure of protection from flash blindness will be afforded, particularly from those weapons which produce extended fireballs.

As a means of providing a measure of protection while more efficient devices were being developed, the Navy considered at one time the use of monocular eyepatches. Figure 3 shows an eyepatch being worn by a pilot during a recent evaluation at the Navy Aerospace Medical Research Department, designed to determine the extent of visual impairment caused by light leaks around the patch. For a time,, there was concern that the afterimage produced in the exposed eye would cause a cortical blurring of the image received from the protected eye, after the patch was removed. Recent testing, however, indicates that this blurring is not sufficient to cause alarm. Useful vision is regained in the protected eye almost immediately following the flash, while vision through the exposed eye may remain impared for many seconds. The major problem with this protective device, however, is that since vision is so critical to most missions, the loss of vision in one eye generally is regarded as only a poor interim solution to the protection problem. However, such patches could be carried by pilots as a means of achieving some measure of protection during emergency conditions.

CURRENT DEVELOPMENT EFFORTS

In 1962, the Air Force was investigating a gold-coated, low-transmission visor for flash blindness protection. In spite of the failure of its earlier fixed-density goggle, the Navy decided also to develop and test a gold-coated visor, in the belief that the different spectral transmission of such a visor, combined with the superior visbility over a goggle system, might make it acceptable. This development program was pursued to completion, with gold-coated visors now being issued to the Fleet as operational items of protective equipment. Figure 4 shows a gold visor for use with the Navy full-pressure suit.

Prior to gold visors' becoming Fleet equipment, an evaluation program was conducted, which consisted basically of asking four questions designed to assess the adequacy of this equipment. The first question was:

1. "Does the equipment afford sufficient protection against flash blindness?"

In answering this question, the first portion of the evaluation involved a theoretical analysis of the protection which would be afforded by visors having one-percent or three-percent photometric transmission. A report by Lappin 1963 presents curves showing retinal irradiance in 150 milliseconds for both low- and high-yield weapons. In computing these irradiances, Lappin assumed an aircraft canopy transmission of 88%, an atmospheric transmission factor of 1.0, an 80% transmission of energy through the ocular media, and a normal daylight pupil of 4 mm. Using the retinal irradiance data of Lappin, Table 1 was prepared, which shows the amount of energy to be received wearing either goggle. If we use the "standard" burn threshold of 0.5 cal/cm^2 described by Bredemeyer, Wiegmann, Bredemeyer, and Blackwell (1963) as a criterion, it can be seen that a one-percent filter will protect against retinal burns under all viewing conditions. A three-percent filter will be effective under all conditions with the possible exception of very high-yield weapons. However, inasmuch as Lappin used a transmission coefficient of 1.0, and thus did not account for energy lost as a function of transmission through the atmosphere, protection against high-yield weapons undoubtedly is adequate, since any nonfatal viewing of such weapons must be done at a distance at which the effects of atmospheric attenuation will be significant.

Inasmuch as the above analysis indicated a three-percent visor would afford substantially the same protection as a one-percent, an empirical test next was conducted to determine the full extent of the protection which a three-percent-transmission visor would provide. In this study, subjects were exposed to a high-energy, short-duration flash believed representative of that which might be experienced from low-yield weapons. A diffuse light was presented which bleached virtually the entire retina. Table 2 shows the characteristics of the flash source and the results which were obtained. As can be seen, flash blindness periods of 42 seconds experienced without protection were reduced to 2.6 seconds when the visor was worn. This latter recovery time was deemed acceptable as a period of visual incapacitation for current Navy missions.

One final question remained concerning the adequency of the protection provided by these visors. When an individual dons a low-transmission visor, he, in effect, moves into a darkened environment in which considerably less light reaches his eyes. Since the human eye responds to a decreased ambient light level by an increase in pupil diameter and retinal sensitivity, the total effectiveness of protective visors might tend to be reduced as the wearer "dark-adapts" behind the visor. Table 3 presents the results of a study conducted to investigate this problem. The light source used was the same as that described in the previous table. Note that for periods of adaption, or visor use, of up to 15 minutes, there is no increase in flash blindness recovery times, and no loss of the effectiveness of the visor.

Both the theoretical and empirical evaluations which were conducted indicate the gold visor to be entirely adequate as a protective device.

The second question was:

2. "Is the equipment compatible with all operational missions?"

A comprehenisve program of flight testing the one-percent gold-plated visors was accomplished by the Naval Air Test Center. Visors were evaluated in flight in five Navy attack fighter and trainer aircraft. The 35 hours of flight tests included day and night flights under visual and instrument conditions and low-level flights beneath an overcast. In these flights tests, under normal daylight conditions, and with the altitude of the sun greater than 30 degrees, adequate lookout doctrine could be maintained and panel instruments could be read satisfactorily. When the altitude of the sun was less than 30 degrees, lookout doctrine and visual flight could be maintained but instrument scan was severely hampered. This was particularly true when the sun was in the forward quadrant relative to the aircraft.

Low-level flight beneath an overcast could be conducted using the visor. However, it was estimated by the test pilots that the visual detection range of airborne targets was reduced from approximately six to three miles. Cockpit instruments were not considered sufficiently readable. Full instrument flight could be accomplished at all times, however, with the instrument panels illuminated by high-intensity thunderstorm lights.

Lookout doctrine, including the identification of lighted ground or airborne targets, was found to be impossible at night. All night flights had to be flown on instruments with the aid of thunderstorm lights.

In short, it was found that all day missions could be flown while using the gold visor, with proper cockpit lighting conditions. Night flights, other than instrument flights, were impossible.

The third question was:

3. "Is the equipment acceptable to the pilots using it?"

A formal test of the acceptance of the gold visor was not conducted. However, informal feedback from pilots who have been issued this visor indicates complete acceptance. Many pilots have expressed a preference for the gold visor over the neutral-gray visor customarily used with the aviator's protective helmet. This preference may be due to the particular spectral bandpass characteristics of the gold visor, which tend to make the world appear brighter as a result of the slight increase of energy transmitted in the 550 millimicron region.

The fourth question asked during the evaluation was:

4. "Does use of the equipment in any manner impair pilot performance or otherwise endanger flight?"

Initial concern was expressed that use of low-transmission visors might cause a small reduction in visual acuity, which would not be noticed by pilots but which would impair effectiveness in air-to-air search. If so, use of the visors would increase the hazards of flight. In order to obtain information on this topic, a field study was conducted to determine the extent to which targets could be detected, under varying conditions of ambient illumination, when wearing visors of 15-, 3-, and 1% transmission, and when not wearing a visor.

Figure 4 presents the results of the target detection study. Although these results are based on only two subjects, there is no evidence that during daylight conditions, use of any of the three visors, even including that which allows only one percent of the visible light to pass, results in any significant decrease in the ability to detect high-contrast targets. However, under low-level lighting conditions, such as might be found at dusk or when flying beneath a solid overcast, there is a substantial reduction in visual acuity when using low-transmission visors. Use of the 15% visor resulted in approximately a twenty percent decrease in the distance at which targets could be detected. Use of the 1% visor resulted in a fifty percent decrease in detection range under the low light level condition. Thus, if a pilot were wearing a three-percent visor while flying beneath an overcast, these results indicate that an aircraft normally detectable at a ten-mile distance would not be detected until approximately six miles away.

The evaluation of the low-transmission gold visor indicates that it is an excellent means of providing flash blindness protection for aviators flying daylight missions. Both theoretical and empirical analyses indicate protection is adequate. Use of the visor does not increase flight hazard and pilots enjoy wearing it. For night missions, the visor is, for all practical purposes, useless. For twilight and other low light level conditions, it should be used with caution because of the attenuation of visibility of distant objects.

While fixed-filter visor systems appear to be satisfactory for day missions, they are, as just noted, unacceptable for night missions. For this reason, considerable effort has gone into the development of "active" devices, which are transparent normally but which "close" when exposed to intense light. One part of the Navy development program has been concerned with use of phototropic materials for inclusion either within goggle systems or for a complete coating of the cockpit canopy. Phototropic materials are transparent solids or liquids which change color and consequently opaqueness when exposed to light. As a rule, they revert to the clear state soon upon removal of the light. Figure 5 shows a prototype phototropic goggle system recently completed and now under evaluation. This system seems to hold considerable promise. The goggles consist primarily of quartz wedges, with a phototropic material held in solution between the wedges. A light source is positioned at the.edge of the quartz lens system, a sensing unit responds to the nuclear burst, and in turn causes the flash to operate and shine down the quartz wedges. The phototropic material then darkens to the stimulation. In the closed state, the phototropic material provides excellent protection against radiation within the visible spectrum. It does not provide complete protection from radiation at frequencies greater or less than this and extra filters are required. The drawback to the use of these filters is that they reduce transmission in the open state. Considerable flight testing remains to be accomplished in order to establish the minimum open-stage transmission allowable for night flight operations.

The most advanced active system at this time is the ELF. ELF stands for Explosively Actuated Light Filter System. The ELF System consists of goggles with clear lenses designed to close automatically upon a signal from a sensing unit. At this time, sensing units under consideration include a silicone cell which responds to a rate of rise of visible energy and an electromagnetic radiation sensor which responds to a very early-time nonvisible energy released by nuclear burst. When an appropriate signal is received, detonators at the top of the lens are activated, driving carbon colloid solution between layers of the lens. Closing time is quite rapid, in the order of 200 microseconds, thus preventing most of the light from a burst from reaching the eyes of the aviator. Opaqueness is quite complete, achieving an optical density of 4.0 or greater, allowing approximately 1/100 of one percent of the visible energy to pass through the lens.

Figure 6 shows the ELF goggle assembly as worn during flight. Quick-release fasteners are seen on either side of the lens, allowing an expended unit to be removed rapidly during flight. Also shown are the sensor, located at the top of the helmet, and the power pack used to provide the detonating signal, worn on the aviator's flying suit.

As might be assumed from the unique characteristics of the ELF System, certain evaluation information is required which has not as yet been obtained. The acceptance which will be accorded this item by Fleet aviators is not known. Susceptibility of the unit to inadvertent activation, such as by flashes of lightning, also is not known with certainty. However, in the event conditions arise which require that operational missions in a nuclear environment be flown at night, a system now is available which will allow adequate night vision and still will protect against the devastating effects of flash blindness.

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TRAINING PROGRAM

The Navy does not feel that protective devices alone are adequate to cope with the flash blindness problem. Flash blindness protective devices, as they are delivered into the Fleet, represent a class of equipment entirely new to pilots. These devices attempt to meet a requirement for which no equipment has been provided. Since these devices are so new and since many of them operate in a strange manner, their introduction into the Fleet must be accompanied by a training program designed to illustrate their method of operation and show how to use them properly. In addition, the flash blindness phenomenon itself must be interpreted both psychologically and physiologically in a manner so that pilots both understand and appreciate the hazards. At this time, all Navy pilots flying attack aircraft participate in a flash blindness training program. The core of this program is the Flash Blindness Indoctrination Trainer shown in Figure 7. This device consists of a high-intensity flash source which simulates the light which would be encountered by a pilot should he by flying within haze conditions or over reflective terrain at the time of the flash.. With this source, it is possible to produce all of the features of flash blindness, intense afterimages, and visual incapacitation, without the risk of permanent damge to the visual system. By actually experiencing flash blindness, a pilot will better appreciate the need for protective devices and should be more highly motivated to use them correctly. And finally, a comprehensive training program has been established so that pilots will understand the flash blindness problem and will use correctly the protective equipment being issued to them.

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TABLE 1

PROTECTION AFFORDED BY
ONE AND THREE PERCENT TRANSMISSION VISORS

	RETINAL IRRADIANCE (Cal/cm²)		
WEAPON YIELD	NO VISOR	ONE %	THREE %
1 KILOTON	4.5 [1]	.05	.15
3 KILOTON	7.5	.08	.24
1 MEGATON	14.0	.14	.43
10 MEGATON	21.0	.21	.63

[1] DATA FROM LAPPIN (1963)

TABLE 2

REDUCTION IN FLASH BLINDNESS RECOVERY TIMES
USING THREE PERCENT TRANSMISSION VISOR

SUBJECT	NORMAL [1] VISION	WEARING [2] VISOR
1	46 SEC.	2.6 SEC.
2	60	3.3
3	36	2.2
4	26	2.2
AVERAGE	42 SEC.	2.6 SEC.

[1] ADAPTING ILLUMINANCE: 25 ft.-c ; TASK ILLUMINANCE: 2 ft.-c

[2] ADAPTING ILLUMINANCE: 25 ft.-c ; TASK ILLUMINANCE :   36 ft.-c

FLASH INTENSITY: 1x 10⁷ft.-L ; DURATION: 3 m sec.

TABLE 3

FLASH BLINDNESS RECOVERY TIMES FOLLOWING
DIFFERENT PERIODS OF VISOR USE
(3 % TRANSMISSION VISOR)

SIMULATED DAYLIGHT COCKPIT CONDITIONS
(ADAPTING LUMINANCE: 200 ft.-L; TASK ILLUMINANCE: 25 ft.-c)

	PERIOD OF VISOR USE		
	10 SEC.	5 MIN.	15 MIN.
SUBJECT 1	2.4	2.0	2.0
2	2.0	2.2	2.0
3	2.1	2.0	2.4
4	2.8	2.1	1.8
AVERAGE	2.3	2.1	2.1

TABLE 4

DETECTION OF HIGH CONTRAST TARGETS
WITH VISORS OF VARYING TRANSMISSION
(2 SUBJECTS)

VISOR TRANSMISSION (PERCENT)	DETECTION DISTANCE (FEET)
DAYLIGHT [1]	
100 (NO VISOR)	1087
15	985
3	1038
1	992
BENEATH SOLID OVERCAST	
100 (NO VISOR)	767
15	618
3	476
1	373

[1] TARGET BACKGROUND LUMINANCE: 1300 ft.-L FOR DAYLIGHT; 40 ft.-L FOR OVERCAST.
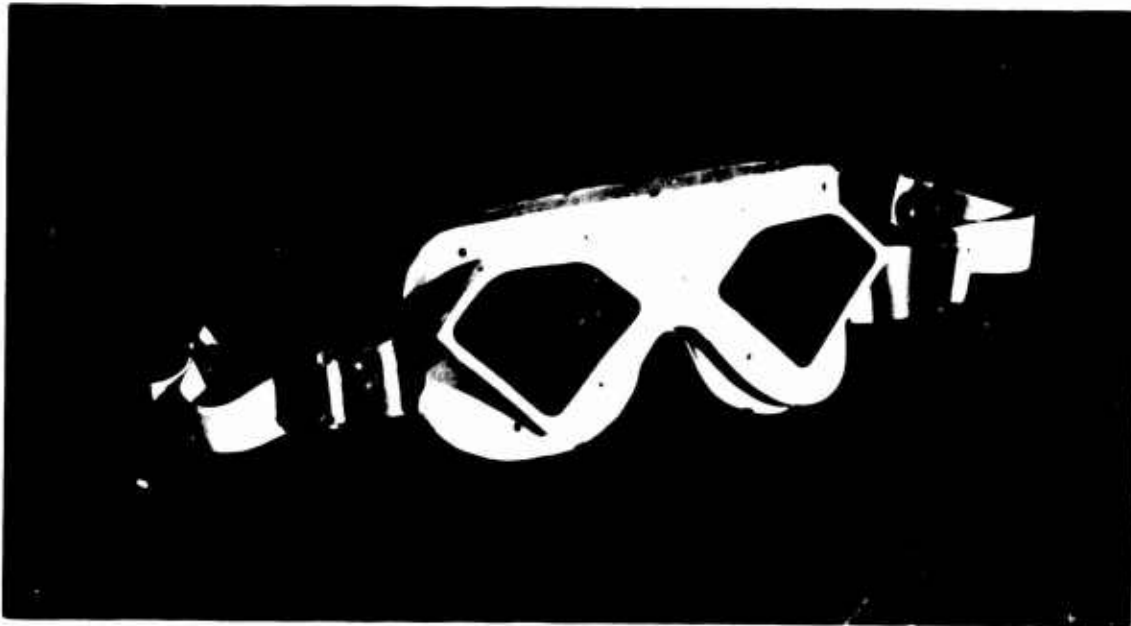
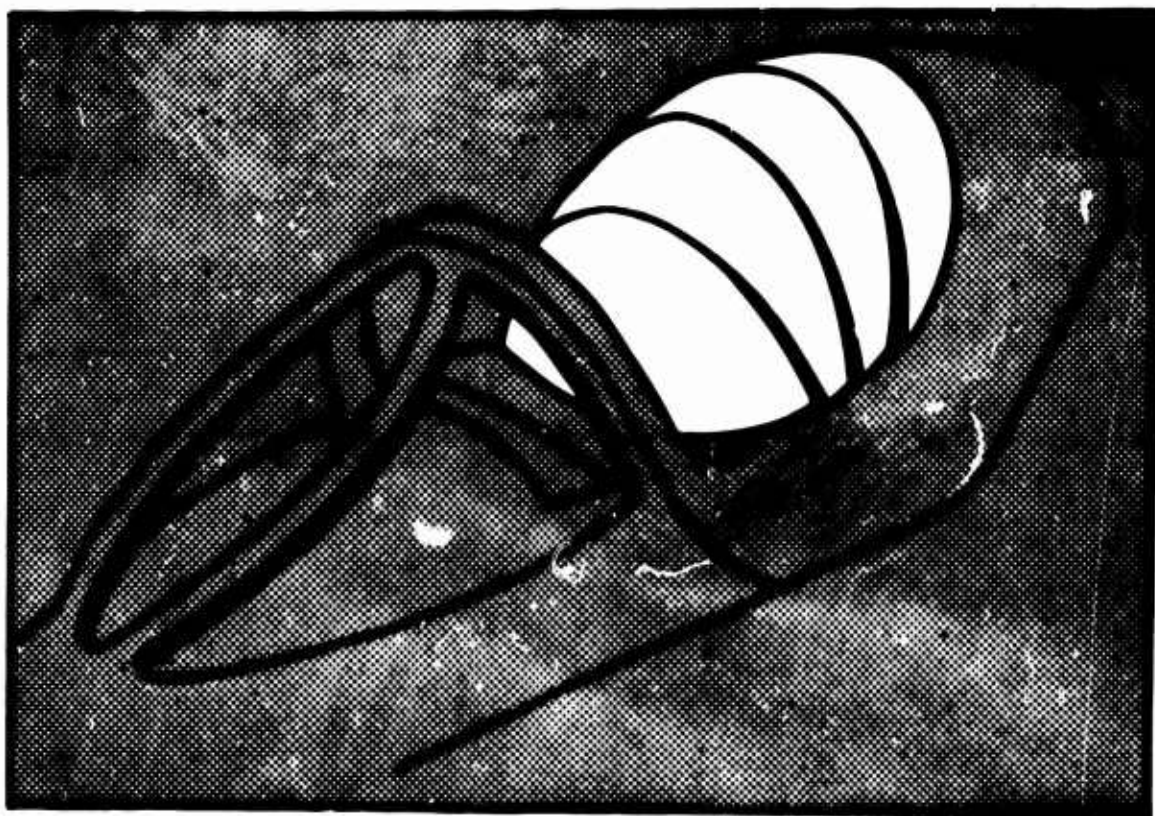Fig. 1   LRFG-58 protective goggle

Fig. 2   Cockpit thermal enclosure

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Fig. 3   Monocular eyepatch

Fig. 4   Gold-coated visor for full pressure suit
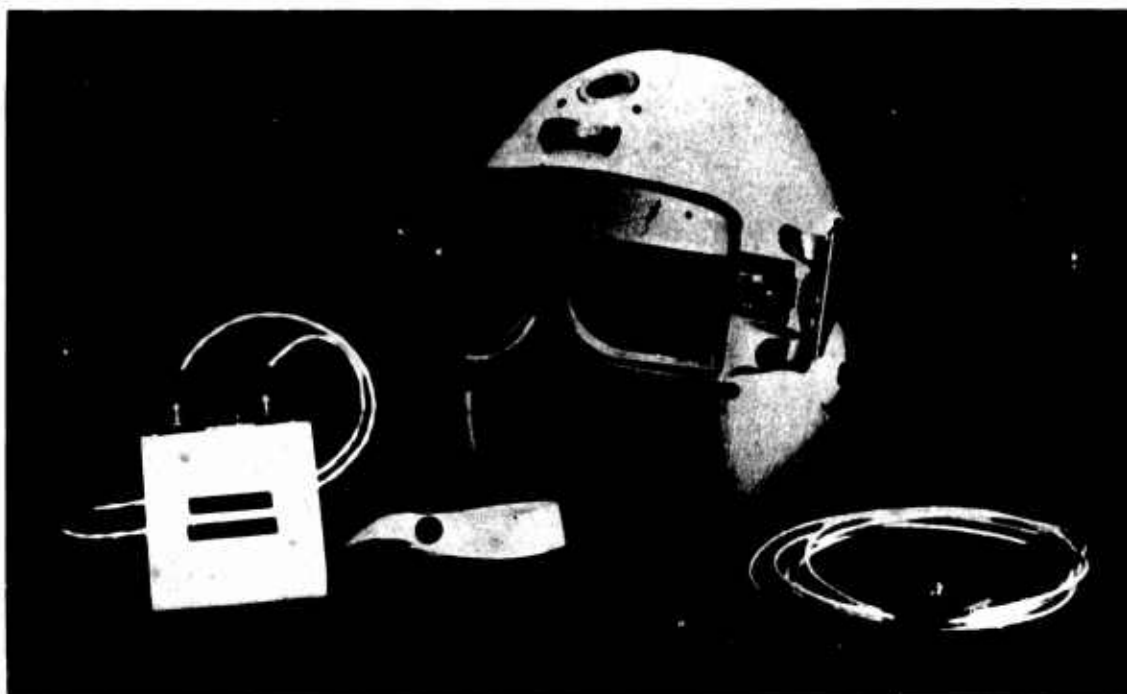
Fig. 5   Phototropic protective goggles
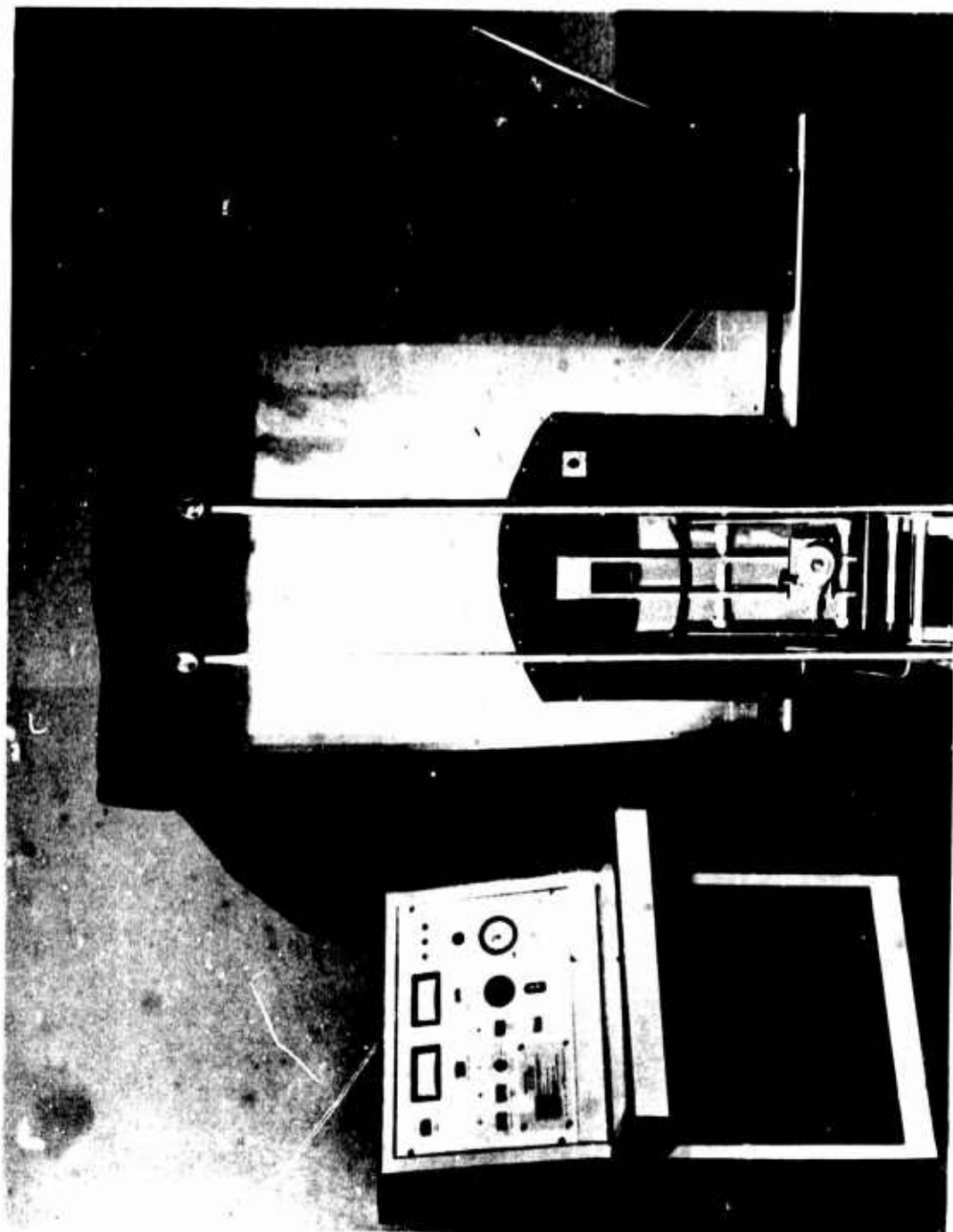

Fig. 6   ELF protective goggle assembly

Fig. 7   Flash blindness indoctrination trainer

PHOTOCHROMIC SUBSTANCES

by

Pharmacien Chemiste Commandant P.J.Douzou

Centre de Recherches des Arimées

The following unscheduled paper on photochromic substances developed in France was
presented by Pharmacien Chimiste Commandant Douzou of the French Army.   He was
introduced by Médecin Général Inspecteur Duval of the French Army

PHOTOCHROMIC SUBSTANCES

P. J. Douzou

Duval The general subject of the symposium of today is certainly that of loss of vision as a result of exposure to light of high intensity. We have touched upon the problem of protection and I would like to have outlined in a few words, research which is being carried out at the centre of research of the Armies in this area. I had already been asked this question on the occasion of the Aircent conference, by Colonel Klotz, and I had given a very brief outline of the problem, but today I thought it better to ask the specialist in this field to talk on the subject and I shall therefore hand over to Pharmacien Chimiste Commandant Douzou who is in charge of the division of biophysics at the research center. He is Master of Research and he is also Professor at Val de Grace, and the work he has carried out in collaboration with the company of St.Gobin, has led to tangible results which I think can as of now, be developed further in a practical sense.

Douzou I am going to try to highlight rapidly the use of photochromic substances against dazzle. I shall therefore deal rapidly with the studies on the problems associated with excitation by light. These substances, which absorb in the medium or near ultra violet, have the property of becoming reversibly coloured. This reversibility is ensured by raising the temperature and the principle characteristics of the substances which we have employed are as follows. The substances become coloured after very brief exposures. One can in principle obtain a marked colour change after a light exposure of 10^{-5} seconds. This speed of reaction is easily explained by the fact that the colouration of these substances is due to an intramolecular change – a change which occurs in the excited state of the molecule. We have a non-coloured substance with an absorption spectrum in the ultra violet and, by means of light excitation, we obtain a coloured substance, and by the action of thermal quanta one obtains a reversible reaction.

On the blackboard we can show diagrammatically and on a basis of energy, that if we plot potential energy against some empirical molecular ordinate, the photochromic process can to a first approximation, be described by the following curves. This would be a curve for a substance which, in its fundamental state was uncoloured. With light excitation, we obtain the excited state of the molecule at a vibration level which is higher than the new molecular configuration. These are typical Morse curves for biatomic molecules. Interatomic distances in angstroem units are on the abscissa. On the ordinate of the graph is, of course, the potential energy of the system. When the molecule therefore reaches the excited state, a conversion takes place within the molecule; a change in structure which acts in different ways according to the chemical structure of the compound. As a result of the excitation we therefore get a new molecular structure towards an unstable transitional coloured state.

We see that when this happens, the effect of temperature on the molecule in
producing a reversal in colour, is easily explained by an action on the molecular
vibration and the crossing of the potential barrier at this point. The recovery time
for the substance to revert to the uncoloured state, varies in response to two
fundamental parameters (a) temperature and (b) the medium.

At very low temperatures, for example that of liquid hydrogen, or liquid helium,
the coloured configurations have an unlimited stability and this is what has enabled
one to suggest that photochromic substances might conceivably be employed as an optical
memory at very low temperatures.

In a viscous medium, one obtains stabilisation of the coloured forms and by
modifying the viscosity and the dielectric con· tant, one can to some extent, regulate
the speed of colour loss of these substances. This speed, for the tests which we have
carried out, can vary from a few tenths of a second up to several seconds, minutes or
hours.

Although many of you may be familiar with photochromic substances, I can perhaps
demonstrate two samples which we prepared in the laboratory. One is already coloured,
the other is fairly clear. These are multiplex transparencies having plasticised
layers in which have been dissolved photochromic substances. We have chosen certain
plastics although we encounter great difficulties in their use. In fact the polymers
which we are using, are often not sufficiently well defined chemically, and it is
difficult to control the degree of purity so that sometimes, rather unexpected results
are obtained.

I shall try to demonstrate this photochromic material to you; it usually works
alright in the laboratory but one never knows in a demonstration before a group of
people. One has to go fairly quickly because the recovery takes place fairly rapidly
whereas the recovery time of this other photochromic substance is of several minutes.
It is of course a function of temperature.

By using multiple sandwich techniques and different phototropic chemicals we have
succeeded in producing neutral density filters. However, the use of photochromic
substances sets us, as it does to all researchers, rather complex problems. These
problems would be difficult to enumerate and still more difficult to discuss in detail.
The first and foremost of these was that of getting sufficiently great optical density.
This is no longer a problem, and I think that all countries studying this problem have
obtained sufficient optical density to ensure eye protection. However, as you
probably know, there exists a problem which is associated with the triggering off of
the photochromic substances. Most frequently one has to effect this trigger by an
auxiliary system, which I am told, unfortunately makes any device envisaged rather
heavy.

From my aspect, that is to say on a physico-chemical basis, the big problem
associated with the use of photochromic substances is that of fatigue. As you
probably know fatigue shows itself by gradual loss of photochromic properties. This
is seen usually as a slowing off of the process, in the first instance and a failure
to realize the full optical density obtainable in the unfatigued state. This problem
of fatigue has been investigated by all workers in this field of phototropic chemistry
and it has been tackled rather unsuccessfully by somewhat empirical methods. At the

present time according to reports in the literature and according to our own personal experiments, it looks as though this problem of fatigue will be at least partially resolved in years to come as a result of a precise and careful study of the reaction mechanisms for the different photochromes utilised.

The diagram which I have produced and which is purely descriptive and qualitative, shows that the electronic and molecular mechanisms acting in photochromism are complex. Secondly, the medium plays a most important role in the intramolecular reaction, and secondary bimolecular or trimolecular reactions giving rise to free radicals and chain reactions are observed in all cases.

To finish I would add that the photochromic substances that I have demonstrated here are derived from the family of spiropyrans. It seems that amongst numerous families of photochromic organic derivatives the spiropyrans have been most frequently employed by researchers. It is these which give rise to the biggest colour changes and intensity changes, in fact the spiropyran derivatives are already commercialised, for example, by the National Cash Register Company in the USA. This therefore is all I had to say. It is of course very little but I think that one can look forward to a good chance of success in protection from the effects of high intensity light by means of photochromic organic derivatives.

HAZARD PREDICTION, SELECTION AND TRAINING

THE RELATIVE DANGER OF RETINAL BURN
AND FLASH BLINDNESS FOR VARIOUS
YIELDS OF NUCLEAR EXPLOSIONS

by

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SUMMARY

The biphasic course of temperature of the nuclear fireball in low
atmospheric explosions makes the danger of retinal burn and of flash
blindness dependent upon the explosive yield. Below 3 kT, roughly,
increasing power leads to increasing danger. Around 10 kT, however,
increasing power only makes a greater part of the flash fall outside
the blink reflex time, so that the visual hazard actually reduces with
increasing power. This paradoxical behaviour might revert to normal
again for explosive yields in the MT range, but for a limited visual
range. This will make then the flash harmless to aircraft outside the
dangerous blast zone. It is therefore concluded that 3 kT explosions
are the most dangerous as regard visual hazards. Detailed examination
of the effects of the high intensity flashes reveals that even the most
dangerous 3 kT explosions will probably not produce retinal burns or
overall flash blindness in day time. Explosions at night, however, may
be expected to produce both of these, but not before 10 msec after the
explosion. Phototropic glasses which "close" within 10 msec to
density 2 may be considered to give adequate protection. This pro-
tection is not sufficient for direct flash blindness by the after image
of the fireball. Protection from this local flash blindness would need
considerably more sophisticated protective techniques which are hardly
worthwhile since, even in the case of a dead ahead explosion,
parafoveal vision will suffice to control the aircraft in an emergency.

THE RELATIVE DANGER OF RETINAL BURN
AND FLASH BLINDNESS FOR VARIOUS
YIELDS OF NUCLEAR EXPLOSIONS

J. J. Vos

1. INTRODUCTION

The visible radiation emitted by the fireball of a nuclear explosion can produce retinal burn and flash blindness.

Though retinal burns are the major effect of the two, flash blindness may sometimes have the more serious consequences. For a pilot, temporary over-all blindness may mean complete inability to control his aircraft and thus be much more dangerous than permanent but local destruction of his retina. The danger of flash blindness seems to be most critical in low altitude flights, where we have to reckon in particular with tactical use of nuclear weapons – i.e. low atmospheric explosions below 1 MT explosive yield. We will restrict our discussion to these situations.

2. DATA ABOUT THE NUCLEAR FLASH

Our knowledge about the nuclear flash mainly comes from the successive editions of Glasstone's "The Effects of Nuclear Weapons"[1]. We cannot consider these data as completely satisfactory as any new edition gives deviating data for the same explosion (Figs. 1 and 2). Earlier[2], we used the data from the 1957 edition which seems to be out of date in view of the 1962 and 1964 editions. The latter editions give two curves, one calculated, one "observed" (inverted comma's by Glasstone). Though it is not specified very satisfactorily what "observed" means, there seems to be no choice assuming that the 1962 observed curve gives the effective black body temperature of the nuclear fireball.

There are two indirect confirmations that this choice is correct. One is that Whiteside's[3] photographic estimation of the effective luminance of the fireball corresponds best with the observed 1962 curve.

Secondly, the 1962 calculated curve inevitably leads to the conclusion that any nuclear explosion, either at daytime or at night, should give a retinal burn.

Since that is certainly not true – a retinal burn by daytime explosions is seldom reported – we have to assume a much lower temperature versus time relation.

The curves of Figures 1 and 2 are valid for a 20 kT explosion in the lower atmosphere.

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Glasstone indicates that we can easily derive from these curves the temperature and radius for other explosive yields by scale transformation. In order to facilitate these scale transformations we plotted in Figures 3 and 4, the temperature (T) versus time (t) and the radius (R) versus time curves (1962, observed) for a 1 kT explosion. The same relations are now useful for any other explosive yield Y (in kT) if we read, instead of t and R :

$$\tau = t_{sec} \cdot Y_{kT}^{-0.5} \quad \text{and} \quad \rho = R_m \cdot Y_{kT}^{-0.4} \; . \tag{1}$$

This means that, the higher the explosive yield, the slower the development of the fireball, but the greater its dimensions. Note that the temperature itself needs no scaling: it is the same for any kind of explosion.

These scaled expressions τ and ρ might be confusing by their more or less abstract significance. We therefore plotted in Figures 3 and 4 and in the subsequent derived curves, all data in terms of t and R for a 1 kT explosion. The scaled notation is added between brackets.

From the temperature course and Planck's law we derived the energy distribution over the spectrum as a function of time. As to the thermal effect, the region between 400 and 1000 nm (nanometers ≡ millimicrons) is of importance as the eye-media only transmit this part of the spectrum. The "effective thermal bandwidth" of the eye is approximately 600 nm (Geeraets et al[4]). As to the visual effect, we took into account the luminosity function $V(\lambda)$, giving the luminous efficiency in lumen/Watt as a function of wavelength:

$$\text{Thermal radiance} \quad N = \int_{\lambda=400}^{1000\,nm} n(\lambda) \; d\lambda \; \text{Watt/m}^2 \text{sr} \; . \tag{2}$$

$$\text{Visual radiance} = \text{luminance} \quad B = \int_{\lambda=0}^{\infty} n(\lambda)V(\lambda) \; d\lambda \; \text{cd/m}^2 \; . \tag{3}$$

with $n(\lambda)$ = radiance per nm according to Planck's law.

In Figure 5 we have plotted N and B as a function of the temperature of a black radiator. By combining these physical data and the technical data about the fireball of Figures 3 and 4 we could construct for a 1 kT explosion

in Figure 6(a) the thermal radiance N
in Figure 6(b) the luminance B   } of the fireball as a function of time.
in Figure 6(c) the luminous intensity I

The luminous intensity is defined as the product of area and luminance. Its value will prove to be of major importance in problems of flash blindness by indirect, scattered light.

In order to evaluate the total effect of the irradiation on the retina we have to know the cumulative effect of the irradiation. We will indicate this cumulative

effect by a flexion ($\sim$) above the respective symbols. In Figure 7(a) we plotted $\widetilde{N} = \int_0^t N\,dt$ = cumulative thermal radiance , in Figure 7(b) we plotted $\widetilde{B} = \int_0^t B\,dt$ = cumulative luminance, and in Figure 7(c) we plotted $\widetilde{I} = \int_0^t I\,dt$ = cumulative luminous intensity - again for $Y = 1\ kT$, but with possibility for generalization.

In order to derive from Figure 7 the cumulative effect up to a certain time t_0 for arbitrary explosive yield Y we have to convert in the following way:

$$\widetilde{N}_{t_0} = \int_{t=0}^{t_0} N\,dt = \int_{\tau=0}^{t_0 Y^{-0.5}} N\,d(\tau Y^{0.5}) = Y^{0.5} \int_{\tau=0}^{t_0 Y^{-0.5}} N\,d\tau \tag{4}$$

$$\widetilde{B}_{t_0} = \int_{t=0}^{t_0} B\,dt = \int_{\tau=0}^{t_0 Y^{-0.5}} B\,d(\tau Y^{0.5}) = Y^{0.5} \int_{\tau=0}^{t_0 Y^{-0.5}} B\,d\tau \tag{5}$$

$$\widetilde{I}_{t_0} = \int_{t=0}^{t_0} I\,dt = \int_{\tau=0}^{t_0 Y^{-0.5}} \pi R^2 B\,d(\tau Y^{0.5}) = Y^{0.5} \int_{\tau=0}^{t_0 Y^{-0.5}} \pi \rho^2 Y^{0.8} B\,dt =$$

$$= Y^{1.3} \int_{\tau=0}^{t_0 Y^{-0.5}} K\,d\tau \tag{6}$$

in which $K = \pi \rho^2 B$ represents the "scaled luminous intensity" (Fig. 7(c)).

The relations $\widetilde{B}_{t_0}$ versus Y and $\widetilde{I}_{t_0}$ versus Y , we have plotted in Figures 8(b) and 8(c) respectively for $t_0 = 10^{-1}$ sec. This time was chosen because the adapting effect of light integrates over a relatively long time so that the effective integration time is determined by the about 0.1 sec blink reaction time of the eye (see Section 4).

As to the thermal irradiance, complete summation of all incident energy combining to produce a retinal burn can only be expected to occur within 10^{-4} sec (Vos[5]), but partial summation occurs over any period within the blink period. We are therefore also interested in cumulative plots for all intermediate times. We therefore drew, in addition to the 0.2 and 0.1 sec integrative curve, curves for a number of relevant smaller integration times as well (Fig.8(a)). To be completely correct, we did not plot

$$\int_0^{t_0} N\,dt \ , \quad \text{but} \quad \left[\int_\tau^{t+t_0} N\,dt \right]_{max}$$

that is the maximum value of the over t_0 accumulated thermal radiance. It is not necessary that this maximum falls at the beginning of the flash. To give an example:

In Figure 7(a) we read for a 1 kT explosion values for the integrated thermal radiance N :

at 10^{-2} sec: 10^4; at 2.10^{-2} sec: 7.10^4; at 3.10^{-2} sec: $2.2.10^5$; at 4.10^{-2} sec: $4.3.10^5$; at 5.10^{-2} sec: 6.10^5 J/m^2 and so on.

Consequently the integrative effect over successive 0.01 sec periods is 10^4, 6×10^4, 15×10^4, 21×10^4, 17×10^4 J/m^2. Evidently the period from 3×10^{-2} to 4×10^{-2} sec gives the maximum integrated thermal radiance. Anticipating the discussion of Figure 8(a) in later sections, we show the curves in dashes over that part where there is no danger of retinal burn, drawn thinly where there is danger at nocturnal explosion when the pupile is wide, and drawn boldly where there is risk, even in daytime explosions, when the pupil is small. For a detailed analysis we refer to Section 5.

A survey of Figure 8(a), 8(b) and 8(c) reveals that all three graphs show a distinct maximum. For retinal burn (a) and direct flash blindness (b) the explosive yields between 1 and 10 kT seem to be most effective. Qualitatively we can understand this in the following way. For small explosive yields, the fireball develops completely within the blink time and consequently the integral is proportional to the scaling factor $\sqrt{Y}$.

For medium explosive yields (between 10 and 100 kT) this effect is superceded by the fact that the second pulse gradually falls outside the blink period with increasing values of Y . Finally, for large yields, the first trend becomes dominant again, but now for the first flash only. For the luminous intensity (c), which governs indirect flash blindness the peak is shifted by a factor of about 3 in the y-axis. This is because the expansion of the fireball with Y gives larger weight to greater values of Y .

3. THE CRITICAL DISTANCE

Though flash blindness and retinal burns can be of vital importance to a pilot, it should be kept in mind that they are only secondary to the directly lethal effects of nuclear explosions. It makes no sense to speak about flash blindness and retinal burns at distances where survival is impossible anyway.

Though Glasstone gives no data about critical distances for aircraft in flight, we can construct on the basis of other data from Glasstone, some curves giving distance as a function of the explosive yield.

As to the nuclear radiation, the critical dose at which a pilot will not be able to perform his mission will be between 100 and 500 REM (Glasstone 1962, Section 11,111). The distances at which these doses are attained are plotted in Figure 9 and on the basis of Glasstone 1962, Section 11.93. As to the heat effects, the critical zone probably lies between the dose for a second degree burn of unprotected skin and that for ignition of household materials (Fig.9). Data are taken from Glasstone 1962, Sections 7.44, 7.46 and 11.63.

The blast zone indicated – between 0.4 and 0.7 lb/in^2 overpressure – is considered to produce "restricted performance" of parked aircraft (Glasstone 1962, Sections 3.66 and 4.50). About damage criteria for flying aircraft we are not informed, but it seems realistic to situate the damage border line not far below this blast zone.

For these reasons we will assume a minimum critical distance S below which we can consider that discussion of flash blindness and retinal burn is pointless:

$$S = 1500 \ Y^{0.33} m \tag{7}$$

a relation plotted in Figure 9 as an interrupted line.

As can be seen from Equation (7) or Figure 9 the critical distance S can grow quite large for high explosive yields. For Y = 1000 kT , S = 15 km . In West-European weather conditions, 20 km visual range at ground level is exceptionally clear. In that case only 10% of the emitted light from an object at 15 km reached the observer. Visual damage due to explosion of such high explosive yields seems to be therefore unlikely. For this reason we will limit our discussion of retinal burn and flash blindness to nuclear explosions below 1000 kT explosive yields.

We now combine Equations (1)

$$R = \rho \ . \ Y^{0.4} m$$

and Equation (7)

$$S = 1500 \ Y^{0.33} m$$

to find the maximum apparent size $\varphi_{max} = 2 R/S$ of the fireball:

$$\varphi_{max} = \frac{2}{1500} \ Y^{0.07} rad = 0.076 \rho Y^{0.07} \text{ degrees } . \tag{8}$$

The relation $\rho(\tau)$ is given in Figure 4, so that we can compute

$$\varphi_{max}(t) = 0.076 \ \rho(\tau \ . \ Y^{-0.5}) Y^{0.07} \text{ degrees} \tag{9}$$

for various values of Y (Fig.10).

An interesting conclusion from this figure is that the fireball never exceeds an apparent size of 5° within 0.1 sec, that is only 1.5% of the total span of the horizon. In other words: the chance that a nuclear weapon, exploding far enough away to give direct harm, produces direct flash blindness or retinal burn in the foveal region is very small. In view of this fact indirect flash blindness gains in importance. This indirect flash blindness is not related to the integrated luminance of the fireball but to the integrated illumination $\tilde{E}$ at the place of the pilot (Section 9):

$$\tilde{E}_{0.1} = \int_{t=0}^{0.1} E \ dt = \frac{1}{L^2} \int_{t=0}^{0.1} I \ dt .$$

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It is interesting to study the course of

$$\widetilde{E}_{max} = \int_{t=0}^{0.1} E_{max}\,dt = \frac{1}{S^2} \int_{t=0}^{0.1} I\,dt \qquad (10)$$

as a function of Y .

Combining Equations (7) and (10) we get

$$\widetilde{E}_{max} = \int_{t=0}^{0.1} I\,dt: 1500^2\,Y^{0.67} = 4.5 \times 10^{-7}\,Y^{-0.67} \int_{t=0}^{0.1} I\,dt \quad . \qquad (11)$$

This relation is plotted in Figure 11 and gives as a result that the danger of indirect flash blindness is predominant only in the region of the small yield weapons with a distinct maximum around the 3 kT yield. Apparently the shift of the peak from 3 kT in Figure 8(b) to 10 kT in Figure 8(c) due to the expansion of the fireball, is compensated by the influence of the larger critical distance S .

Summarizing we can state that, whether we speak about retinal burn, direct or indirect flash blindness, the 3 kT yield is the most dangerous.

4. THE PUPIL AND THE BLINKING REFLEX

The eye is protected against excessive irradiation by blinking and by contraction of the pupil. The latter is a relatively slow process and gives almost no protection against a sudden flash. However, the pupil area at the moment of the explosion is a strong co-determinant to the retinal irradiation. For this reason it is necessary to discuss separately flash blindness and retinal burn for nocturnal and day explosions.

On the average one can assume a nocturnal pupil diameter of about 7 mm and a daytime size of about 3 mm.

If one is interested in flash blindness of the cone receptor system which largely takes care of our reading facilities, then the effect of pupil contraction is less dramatic than suggested by the ratio $7^2/2^2 \simeq 5$. The specific properties of the cone system are such that the edge of the pupil does contribute to the visual effect in a reduced way (Stiles and Crawford[6]). For cone vision, the pupil has as it were an average luminous efficiency $\bar{\eta}$ which decreases with increasing pupil size d : at d = 3 mm $\bar{\eta} = 0.9$, at d = 7 mm $\bar{\eta} = 0.5$ for the average man. That means that for visual effects, the above mentioned ratio of nocturnal and diurnal pupil apertures should be reduced to

$$\frac{7^2 \times 0.5}{3^2 \times 0.9} \simeq 3 \quad .$$

The blink reflex works relatively quickly. Gerathewohl and Strughold[7] give 0.18 sec for the closure time. More recent data from Smith[8] show that an alert and under-standing subject manages to shut his eyes in 0.10 sec. Alert and understanding means

that he knows that a flash can be expected and that the best reaction is to shut his
eyes. Our own investigations have indicated that we have to reckon with a wide
variation in blink times between subjects. We will assume a "blink period" of
0.1 sec but now and then discuss the influence of a longer blink time up to 0.2 sec.

5. THE DANGER OF RETINAL BURN

It makes no sense to study flash blindness where a retinal burn dominates the
picture. The threshold thermal dose for retinal burns depends on the time of
irradiation and on the size of the retinal image (Ham et al[9,10]). Theoretically
(Vos[5]) one can treat the image size as infinitely large for times

$$t_{sec} < 36 \, d^2 cm \tag{12}$$

in which d = diameter of the retinal image . Now

$$n \, d/D = \varphi_{rad} = \frac{\pi}{180} \varphi_{degrees}$$

with D = focal length of the human eye $\simeq 2$ cm and n = refractive index of the eye
media $\simeq 4/3$, so that for

$$t_{sec} < 0.025 \, \varphi_{degrees}^2 \tag{13}$$

the image can be treated as infinitely large. The relation $t = 0.025 \, \varphi_{degrees}^2$ is
plotted in Figure 10 as an interrupted line. It is evident that at the critical
distance S the fireball behaves "opto-thermally" as infinitely large at any stage
of its growth. This remains true for considerably larger distances than the critical
distance S , in particular for the lower explosive yields. We will therefore discuss
the danger of retinal burn under the assumption that the fireball is large. For that
situation the critical dose Q versus time relation is given by Figure 12. The
relation between $Q(J/m^2)$ and $N(J/m^2)$ is given by

$$N = \frac{Q}{\omega_{pupil} \cdot n_{eye \, media}^2} \tag{14}$$

in which ω_{pupil} = solid angle of the pupil from the retinal image .

Taking $n = 4/3$ and

$$\omega_{pupil} = \frac{\pi \cdot 1.6^2}{20^2} \simeq 0.020 \text{ sr at daytime, and}$$

$$\omega_{pupil} = \frac{\pi \cdot 3.5^2}{20^2} \simeq 0.1 \text{ sr at night,}$$

we find for any time of irradiation, nocturnal and diurnal values of the integrated
thermal radiance (Table I) which should be compared with the curves of the actually
emitted radiance of Figure 8(a).

TABLE I

Time (sec)	Critical thermal dose N in J/m^2 sr	
	at daytime	at night
10^{-4}	$2.4 \ 10^5$	$4.8 \ 10^4$
3.10^{-4}	$2.7 \ 10^5$	$5.4 \ 10^4$
10^{-3}	$3.6 \ 10^5$	$7.2 \ 10^4$
3.10^{-3}	$5.2 \ 10^5$	$1.0 \ 10^5$
10^{-2}	$8.0 \ 10^5$	$1.6 \ 10^5$
10^{-1}	$1.7 \ 10^6$	$3.4 \ 10^5$
2.10^{-1}	$2.2 \ 10^6$	$4.3 \ 10^5$

In view of these tabulated values, it is evident in Figure 8(a) that the critical
dose is only exceptionally exceeded at daytime within the blink period. Nocturnal
explosions below 30 kT or above 700 kT must be considered harmful from the retinal
burn aspect.

A clearer picture is given in Figure 13 which shows what happens at successive
stages of the development of the nuclear flash for various explosive yields.

We will discuss it by means of three examples. A 10 kT fireball becomes visible
after 6.10^{-5} sec, but during the first flash nothing happens. Only at the end of the
second flash, after 0.06 sec, the burn threshold is exceeded when the explosion takes
place at night. In daytime, the burn threshold is reached after 0.14 sec, that is
just when the blink reaction may become effective. A 1000 kT fireball becomes visible
after 6.10^{-4} sec and produces a burn between 6.10^{-3} and 3.10^{-2} sec at night. The
second flash comes too late to be harmful either by day or by night. For explosions
between 30 and 500 kT the first flash is too short and the second flash comes too
late to produce burns at all. Figure 13 gives no indication about the seriousness of
the burns. When we consider Figures 13 and 8(a) together, we can see that at 10^{-1} kT,
the threshold dose is hardly exceeded, so that probably the damage will be small.
At 3 kT, the threshold dose is finally exceeded by a factor 4 so that the damage
might be serious and permanent.

Summarizing our findings, we can state:

    (a) Explosions by day will seldom if ever produce retinal burns.

    (b) Explosions by night will produce retinal burns when the explosive yield is
        smaller than 30 kT or larger than 500 kT. Explosions between 30 and 500 kT
        will give no retinal burn.

    (c) Absorbing glasses which reduce the intensity by a factor 5 protect the eye
        against retinal burns at night. To be safe and to account for small variations
        in the standard blink reflex time, a reduction factor 10 might be recommended.

    (d) Automatic protecting devices which work with electro-mechanical shutters or
        phototropic materials protect against retinal burns up to 1000 kT explosions

when their closing time is not longer than $5 \cdot 10^{-3}$ sec. A closing time of 10^{-2} sec gives protection from retinal burns from explosions up to 500 kT.

6. RECOVERY TIME AFTER FLASH BLINDNESS

A great deal has been published on the recovery of visual performance after flash blindness. Understandably in view of the many parameters involved, it is difficult to bring all data together to get one simple picture. Recovery times have been measured for peripheral and for central vision, for various kinds of targets (detection of a white spot, reading of meters, recognition of the orientation of acuity gratings and so on) and with various types of flash stimuli. Starting from the assumption that the Air Force is mainly interested in the recovery of central vision so that reading of instruments becomes possible again, we have gathered data from literature only in this direction.

The number of ways one can express the flash intensity is really embarrassing. We have tried to express all available relevant data into one unit of retinal exposure ϵ : the effective troland second ($trol_{eff}$. sec). The troland is the unit of retinal illumination; one can get the numerical value by multiplying the luminance of the object in cd/π^2 by the area of the pupil in mm^2. The effective troland is a refined version of it as it accounts for the reduced luminous efficiency of the pupil border in cone vision. One gets the effective retinal illumination in effective trolands by multiplying the object luminance in cd/m^2 with the effective pupil area $\bar{\eta} . \pi r^2$ (see Section 4) in mm^2.

The effective retinal exposure in $trol_{eff}$sec is obtained by multiplying this number with the flash time in seconds. The implicit assumption is that only the product of I and t is relevant for the adapting effect. As a matter of fact this is confirmed by many investigators up to times of the order of seconds. Only relatively recently deviations from the reciprocal relationship between I and t have been found in the microseconds range (Hill and Chisum[11]). Though the theoretical implications of this finding might be great, its practical significance in problems of flash blindness seems to be small. We will not extensively discuss here the various, many times contradictory, literature data, but at once produce a final graph which, in our opinion, represents the best compromise of all data available[12] (Fig.14).

7. FLASH BLINDNESS IN THE DIRECT IMAGE

In Section 5 we concluded that even in the worst situation, the retinal burn level is not reached at daytime and that we can avoid retinal burn at night by wearing absorbing glasses with a transmittance of some 10% or with automatic closing devices.

It will be evident however that in these marginal situations the total amount of light entering the eye will be so large that marked direct flash blindness is produced. To give a more quantitative idea:

at night, when the pupil is 7 mm wide, and with a 10% filter:

$$\epsilon = 10\% \times \frac{\pi}{4} . 7^2 \times (\bar{\eta} = 0.5) \times 4 . 10^8 = 8 . 10^8 \ trol_{eff}sec.$$

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Here $4 . 10^8$ is the maximum integrated luminance according to Figure 8(b). In Figure 14 one can check that this level is so high that no experimental data are available.

At daytime, with a 3 mm pupil and without filter:

$$\epsilon \doteq \frac{\pi}{4} . 3^2 \times (\overline{\eta} = 0.9) \times 4 . 10^8 = 2.5 \ 10^9 \ \text{trol}_{\text{eff}}\text{sec}.$$

Since this figure holds for daytime, we can not use Figure 14 to evaluate it in terms of recovery times, but we can compare it to the situation of looking into the sun.

The brightness of the sun's disc is 1.2×10^9 cd/m^2, so if we look straight into it, assuming that the pupil is small,

$$\epsilon_{\text{sun}} = \frac{\pi}{4} . 2^2 \times (\overline{\eta} = 1) \times 1.2 \ 10^9 \times \tau = 3.6 \ 10^9 \ \tau \ \text{trol}_{\text{eff}}\text{sec},$$

if τ represents the time of exposure.

We conclude that the maximum flash blindness, due to a nuclear explosion by day corresponds to looking straight into the sun for 0.7 sec. Anyone who has looked into the much fainter setting sun during a single glance realizes that the after-image must be extraordinarily strong. The use of automatic shutters reduces the light incidence in another way, but it will be clear that the closing time of 10^{-2} sec, which just prevents a burn in most situations, again leads to values for direct exposure ϵ of the order of 10^9 trol$_{\text{eff}}$sec. For a closing time of 10^{-3} sec one easily computes with Equation (5) that B is reduced to about $5 . 10^6$ cd s c/m^2 -- thus giving a nocturnal exposure $\epsilon \simeq 10^8$ trol$_{\text{eff}}$sec. At this point we come to a range of more physiological exposures.

8. THE RETINAL EXPOSURE BY INDIRECT FLASH

Summarizing the problem of retinal burn and direct flash blindness, we can say that, without protection visual impairment is to be expected both by day and night explosions, but that the chance of this occurring in the fovea is relatively small. The reverse holds for indirect flash blindness as will be shown below. The indirect light covers the whole visual field, and one cannot discuss it in terms of chance. However the level will be much lower than with direct illumination and one can meet the visual handicap by relatively simple measures.

As to the indirect light, we can treat the fireball as a point source with luminous intensity I(t) . The relevant parameter then, is the integrated intensity $\Upsilon_{0.1}$ of Figure 8(c). The indirect blinding effect is strongly dependent on the distance of the fireball in contradistinction to the direct effect. It follows the normal optical quadratic reduction law $\sim 1/L^2$, so that the essential characteristic is the illumination $\widetilde{E} = \widetilde{\Upsilon}/L_2$. In Section 3 (Fig.11) we pointed out that $\widetilde{E}$ is large in particular in the 1 to 10 kT range, due to the critical distance effect.

The effect is strongly dependent on the direction of the fireball in (or outside) the field of view. The important parameter therefore is the angle between the direction

of gaze and the direction of the fireball. We again assume here that essential for visual performance, is the recovery of central vision.

Three main components of indirect light can be indicated:

(i) Entoptic straylight only occurs when the fireball is in the field of view so that direct light enters the eye. It is scattered in the ocular media and produces a masking veil of entoptic straylight.

(ii) Atmospheric straylight occurs both with the fireball in the field of view and outside, although it is considerably weaker in the latter case.

(iii) Reflected light. The most important source is cloud, which has a high reflectivity and can cover large parts of the visual field.

Quantitatively these three components behave according to the formulae given in Table II. These formulae are derived and discussed in an earlier published report[2].

TABLE II

	Daytime	*Night-time*
$\epsilon_{entoptic}$	$(100 \ S^2/L^2\vartheta^2)\widehat{E}$	$(300 \ S^2/L^2\vartheta^2)\widehat{E}$
$\epsilon_{atmospheric \ (forw.)}$	$(35 \ S^2/L^2\vartheta)\widehat{E}$	$(100 \ S^2/L^2\vartheta)\widehat{E}$
$\epsilon_{atmospheric \ (backw.)}$	$(0.03 \ S^2/L^2)\widehat{E}$	$(0.1 \ S^2/L^2)\widehat{E}$
ϵ_{clouds}	$(2 \ S^2/L^2)\widehat{E}$	$(6 \ S^2/L^2)\widehat{E}$

(ϵ in $trol_{eff}$sec; $\widetilde{E}$ in lux sec according Figure 11; and ϑ in degrees)

These relations are approximative descriptions of course and can be assumed to be valid for values of L (the distance of the fireball to the observer or the cloud respectively) well within, but not negligible compared with the visual range and for $\vartheta < 20^{\circ}$.

It will be evident that the tabulated formulae cover a wide range of retinal exposures. Nevertheless it is useful to evaluate them numerically for a few values of L and ϑ in order to give some limits and in order to assess the hazard.

We first compute ϵ_{total} for L = S (the minimum distance for which computation make sense and $\vartheta = 3^{\circ}$, 10°, 20° and 180° . $\vartheta = 3^{\circ}$ is the minimum angular distance for which computation makes sense as the fireball itself has a maximum radius of almost 3° at critical distance. We make the computation for nocturnal explosions.

$$\epsilon_{3^{\circ}} = (300/9)\widetilde{E}_s + [(100/3)\widetilde{E}_s \quad or \quad 6 \ \widetilde{E}_s] \simeq 70 \ \widetilde{E}_s$$

$$\epsilon_{10^{\circ}} = (300/100)\widetilde{E}_s + [(100/10)\widetilde{E}_s \quad or \quad 6 \ \widetilde{E}_s] \simeq 13 \ \widetilde{E}_s$$

$$\epsilon_{20^{\circ}} = (300/400)\widetilde{E}_s + [(100/20)\widetilde{E}_s \quad or \quad 6 \ \widetilde{E}_s] \simeq 7 \ \widetilde{E}_s$$

$$\epsilon_{180^{\circ}} = 0.1 \ \widetilde{E}_s + 6 \ \widetilde{E}_s \simeq 6 \ \widetilde{E}_s$$

The either/or condition means that we assumed either clouds or haze/fog as a limiting factor to the visibility. In order to maximize the effect on the retinal exposure, we always chose the larger of the two values. Daytime values are smaller than those indicated by a factor 3. Values for explosions at larger distances can be found by multiplying these values with $(S/L)^2$, S being given by Equation (7).

According to Figure 11 the maximum value of $\tilde{E}_s = 2 \times 10^6$ lux sec, for a 3 kT explosion, so that $\epsilon_{max} \simeq 70 \times 2 \times 10^6 \simeq 1.4 \; 10^8$ $trol_{eff}$ sec . This value lies just below the retinal burn level (Fig. 12) and thus retinal burn in indirect light will not occur. It lies, however, above the experimental range of flash blindness investigations (Fig. 14) so that extraordinarily strong flash blindness should be expected.

But it makes no sense to concentrate completely on maximum effects. It is better to consider the effects in terms of chance. Now, a 20^0 field of view covers only 10% of the horizon, so that in 90% of the cases an explosion will cause flash blindness of less than $7 \; E_s$ retinal exposure. We assumed here that both the pilots viewing direction, and the fireball are restricted to one horizontal plane. If we allow some freedom for one or both of them in the vertical direction, the 10% value is considerably lower.

Further we can assume that the chance that a nuclear weapon explodes within distance S, is small. If not, discussion of the flash blindness problem would not be the most urgent question.

Let us assume that this chance is C . Correctly defined, C represents the total chance that during the flight a nuclear weapon explodes within the critical distance S . A short calculation of probabilities shows that the most probable distance for the nearest explosion is then given by

$$L_{pr} = \frac{0.7 \; S}{\sqrt{C}} \tag{15}$$

as can be proved as follows.

Suppose the chance that a bomb explodes within an area $d\sigma$ is $Pd\sigma$. Then the chance that there is no explosion within σ is given by

$$(1 - Pd\sigma)^{\sigma/d\sigma} = (1 - Pd\sigma)^{(1/Pd\sigma)\sigma P} = e^{-\sigma P} \quad \text{in the limit} .$$

The chance that there is an explosion within distance S is therefore

$$1 - \sigma^{-\pi S^2 P} = C .$$

Then
$$P = \frac{\log_e 1/(1 - C)}{\pi S^2} \simeq C/\pi S^2 \quad \text{for} \quad C \ll 1 .$$

The chance that the nearest explosion falls between L and dL is now

$$e^{-\pi L^2 P} . 2\pi LP dl .$$

Differentiation to L gives as the most probable value of L

$$L_{pr} = \frac{1}{\sqrt{2\pi P}} = \frac{S}{\sqrt{2C}} = \frac{0.7\,S}{\sqrt{C}} \quad .$$

If we assume $C = 0.1$, which means a small but not negligible chance of directly lethal effects of the explosion, then $L \simeq 2S$. Accordingly the retinal exposure to be expected is smaller than $7\,E_s$ by a factor 4. If we finally assume that we have to expect mainly 3 kT explosions which are most harmful according to Figure 11, then we arrive at an "expectance value"

$$\epsilon_{exp} \simeq 4 \times 10^6 \text{ trol}_{eff}\text{sec} \quad .$$

Summarizing its significance we can say that ϵ_{exp} represents a value of retinal exposure which might well be produced by indirect light. Lower values will occur of course, but we are interested in some kind of effective maximum. Higher values cannot be excluded either, but the chance that they may occur is relatively small.

The above indicated value holds for nocturnal explosions. Its effect will be evaluated after a discussion of admissable recovery times in regard to the pilot's task. By day the value is lower by a factor 3 because of pupil size. We can evaluate its effect as follows. The luminance of the daylight sky is of the order of 3×10^3 cd/m^2, corresponding to a daylight retinal illumination of 2×10^4 trol$_{eff}$. We look continuously to this luminance level, so that the integration time will be large. How large is not well known, but experiments on dark adaptation after various times of pre-adaptation (Wolf and Ziegler[16]) suggest at least incomplete summation to times up to 100 sec. Let us be safe and take $t_{eff_s} = 10$ sec. Then the effective retinal exposure by the daylight sky will be 2×10^5 trol$_{eff}$sec — a value which is only 5 times smaller than the flash exposure. In view of the extremely rapid adaptation at these high levels, this retinal exposure will not give any notable visual impairment.

In the preceding sections we have repeatedly mentioned the use of automatic shutters in front of the eye. It is interesting to have a look to what happens if the effective opening time of the eye is reduced to a time, t_0 , instead of 0.1 sec. We compute

$$\ddot{E}_{t_0,s} = \ddot{I}_{t_0} : S^2 = Y^{1.3} \int_0^{t_0 Y^{-0.5}} K\,d\tau : 1500^2\,Y^{0.67} = 4.5 \times 10^{-7}\,Y^{0.67} \int_0^{t_0 Y^{-0.5}} K\,d\tau$$

and

$$\epsilon_{exp.\,t_0} = 7\,\widetilde{E}_{t_0} \times (S/L_{pr})^2 = \frac{7}{4}\,\widetilde{E}_{t_0,s}$$

or

$$\epsilon_{exp.\,t_0} = 8 \times 10^{-7}\,Y^{0.67} \int_0^{t_0 Y^{-0.5}} K\,d\tau \quad . \tag{16}$$

With this formula, together with the graphical data in Figure 7(c) we computed the maximum value of ϵ_{exp} for the range of Y-values between 0.1 and 1000 kT:

$$\text{for} \quad t_0 \; = \; 10^{-2} \text{ sec} \qquad \epsilon_{exp} \; = \; 1.2 \times 10^5 \text{ trol}_{eff}\text{sec}$$

$$\text{for} \quad t_0 \; = \; 3 \times 10^{-3} \text{ sec} \qquad \epsilon_{exp} \; = \; 1.1 \times 10^4 \text{ trol}_{eff}\text{sec}$$

$$\text{for} \quad t_0 \; = \; 10^{-3} \text{ sec} \qquad \epsilon_{exp} \; = \; 2.5 \times 10^3 \text{ trol}_{eff}\text{sec} \; .$$

To give some idea of the significance of these levels we compute the retinal illumination for the full moon which has a luminance of 2.6×10^3 cd/m^2. The corresponding retinal exposure is

$$\frac{\pi}{4} . \, 7^2 \times (\bar{\eta} = 0.5) \times 2.6 \times 10^{-3} \; = \; 5 \times 10^4 \text{ trol}_{eff} \, ,$$

so that for a 0.1 sec glance

$$\epsilon_{moon} \; = \; 5000 \text{ trol}_{eff}\text{sec} \; .$$

It is evident that the automatic shutter dramatically reduces the indirect flash blindness.

9. REQUIRED LEVELS OF PANEL ILLUMINATION

In contradistinction to retinal burn, flash blindness does not permanently impair visual performance. There is a gradual recovery and whether a certain degree of flash blindness can be tolerated depends on the length of the blind period accepted. This period, in turn, will depend on the visual task concerned. We will not discuss this problem in detail here, but simply postulate a blind period of 10 seconds. This value is based[12] on the assumed task of high speed low altitude flying.

In Figure 14 we can now indicate two lines, one parallel to the abscissa giving the expectable flash exposure with the naked eye, and one parallel to the ordinate giving the admissible recovery period, which together enclose the effective exposure/time area.

According to the curves drawn, the luminance of the panel instruments may not go below 30 cd/m^2. With "the" luminance we mean the luminance of the brightest parts such as numerals and markings.

This value will easily be attained by day, so that flash blindness by day is not to be feared. For flights at night we are dealing with artificially illuminated panels which normally have a luminance between 0.1 and 1 cd/m^2 in order to avoid interference with night vision.

Consequently the panel illumination should be drastically raised. In principle this need not give rise to any difficulty. The 30 cd/m^2 luminance need not cover the whole panel but only the vital instruments. Let us assume that these vital instruments together cover an area of $20 \times 20 = 400$ cm^2. A luminance of 30 cd/m^2 of white objects is produced by an illumination of about 150 lux. 150 lux over 400 cm^2 requires a directional light source of $150 \times 4.10^{-2} = 6$ lm which can be produced, with proper focussing, by a few Watts of incandescent light It will be clear that no difficulties exist in attaining the 30 cd/m^2 or even a higher luminance level. If we

use the reduced values of ϵ_{exp} for the automatically protected eye (Section 8, end) it will be evident that additional panel illumination is completely unnecessary.

10. PROTECTION

In the foregoing sections we repeatedly mentioned means of protection and their effect on retinal burns, and on direct and indirect flash blindness. It is time now to survey these scattered data as a whole.

We have found that neither retinal burn nor indirect flash blindness is a real problem by day. The only danger comes from the strong after-image of the fireball which locally impairs vision. If it falls in the periphery of the field of view, it will not notably affect visual performance. But even if it happens to fall on the fovea, instrument reading and field scanning with parafoveal vision remain possible. It seems doubtful whether this small chance of moderate visual impairment justifies protective measures. This holds the more where visors, as in normal use in flying, give some protection against this flash blindness.

At night, there is a greater risk of retinal burn – though again, there is small risk that it occurs in the foveal region – and one can say that any nuclear explosion produces a serious indirect flash blindness.

Protection seems to be mandatory. Three ways seem to be open:

(a) Wearing absorbing glasses. Reduction by a factor 10 seems to be sufficient to eliminate retinal burns. However, it will be clear that this is a solution which is quite impractical with night operations.

(b) Additional panel illumination. It is demonstrated that such additional illumination does not meet any great technical difficulties. It does not help however against retinal burn and restores only foveal vision, that is, for instrument flying. Vision of the outside world may be absent for a long time.

(c) Automatic closing devices. It is shown that a closing time of 10^{-2} sec gives protection from retinal burns for all explosive yields except the very high ones, and damage from the high explosive yield explosions is only to be expected with exceptionally clear weather. Moreover indirect flash blindness is reduced to practically harmless levels as regards foveal vision. When the closing time is further reduced recovery of a considerable degree of peripheral vision during the flight time seems to be possible. The after-image of the fireball remains visible notwithstanding all these protecting devices, but if it falls in the foveal region, parafoveal instrument reading seems to be quite possible in view of the small area covered by the nuclear flash.

11. CONCLUSIONS AND RECOMMENDATIONS

(a) By day, nuclear flashes have little visual significance. The worst situation to be expected is a nuclear flash right in the line of sight of the pilot, and even in that unlikely situation the pilot can keep reading his instruments and looking around without too much difficulty. Protection seems to be superfluous.

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(b) At night he runs the risk of a retinal burn, which is a serious condition if it happens to occur foveally. He will then experience an overall flash blindness which may prevent instrument reading during tens of seconds or more and of course completely blocks night vision. Protection seems to be mandatory.

(c) Two adequate means of protection seem to be present. The best protection is offered by automatically closing devices such as electromechanical goggles or phototropic materials. The requirements are not exceptional. A closing time of 10^{-2} sec to density 2 gives great help already. With this, a retinal burn is prevented and instrument reading can be maintained without additional illumination, provided the fireball is not seen with central vision. Shorter times are of course better. A 10^{-3} closure time even cuts down the indirectly incident light to levels where recovery of peripheral vision within acceptable time limits seem to be possible. If this solution 's not possible for technical, psychological or other reasons, additional emergency panel illumination must be thought mandatory. Technically, this solution should meet no difficulties, but of course it only helps to avoid the most disastrous effects of nuclear flash blindness and does not give any protection against retinal burns.

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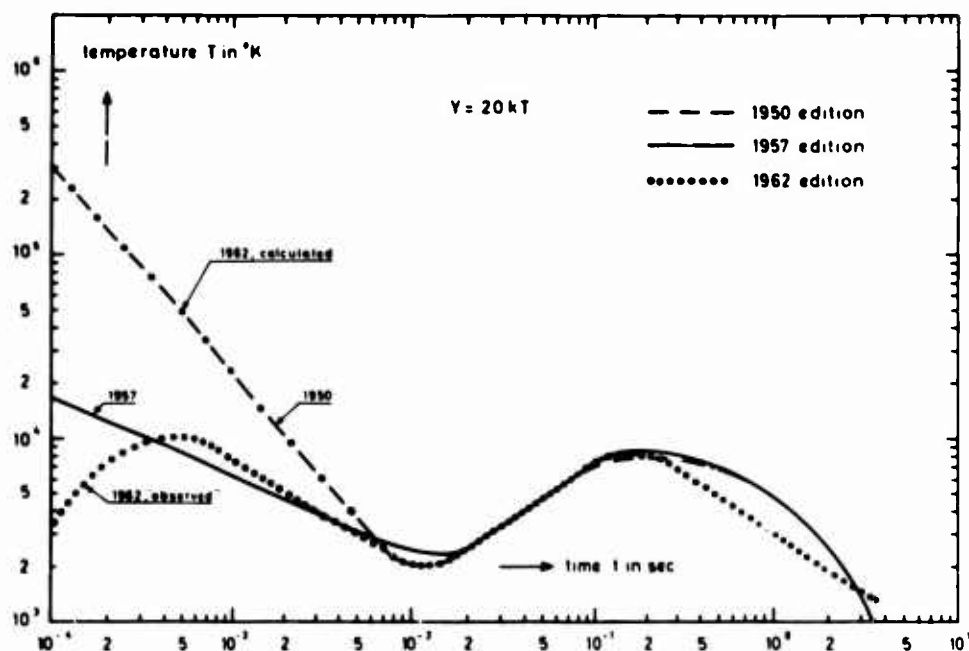
Fig. 1   The temperature course of the fireball after a 20 kT nuclear explosion
according to successive editions of Glasstone's "The effects of
nuclear weapons[1]"
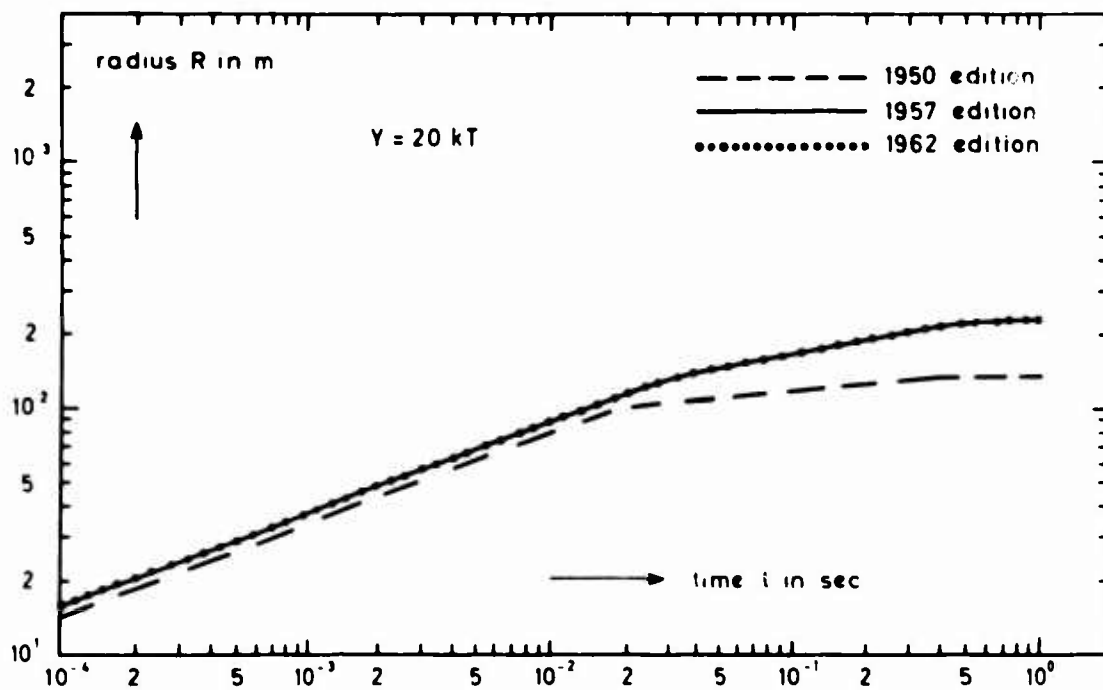
Fig. 2   The growth of the fireball after a 20 kT nuclear explosion according to
successive editions of Glasstone's "The effects of nuclear weapons"[1]
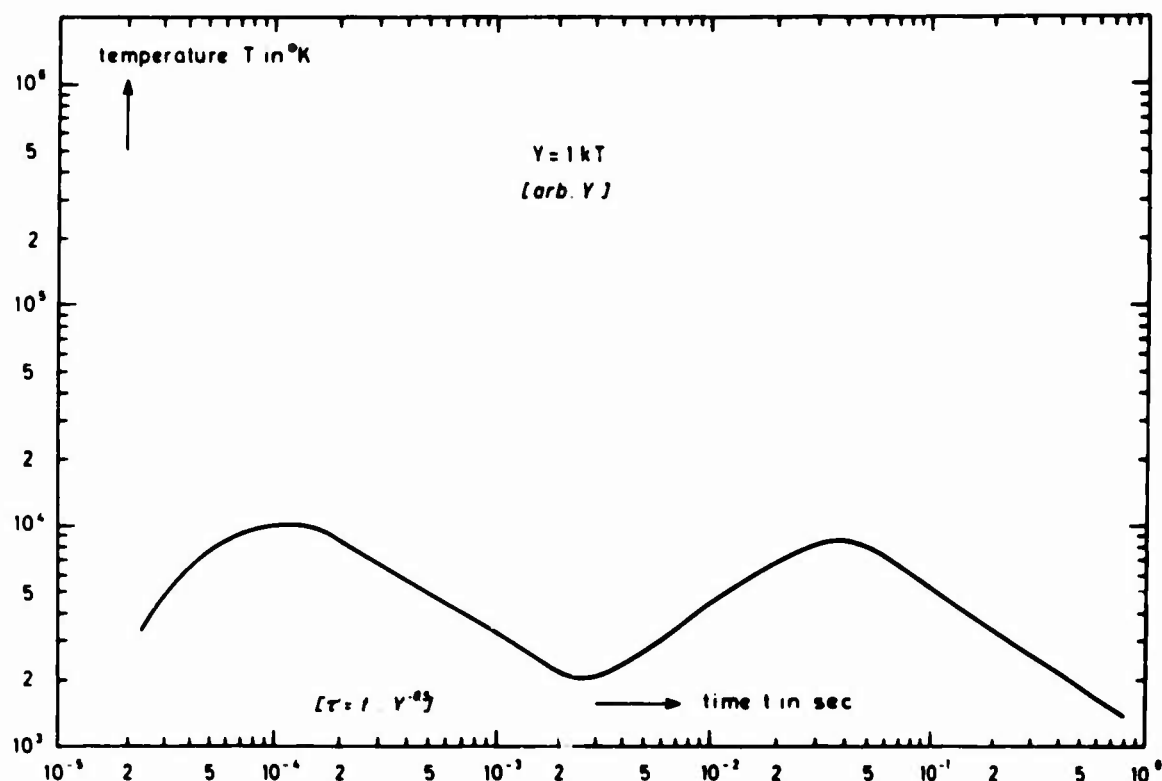
Fig. 3 The assumed temperature versus time relation for the fireball after a 1 kT explosion. The same course holds for other explosive yields Y if we read $\tau = t . Y^{-0.5}$ instead of t along the abscissa
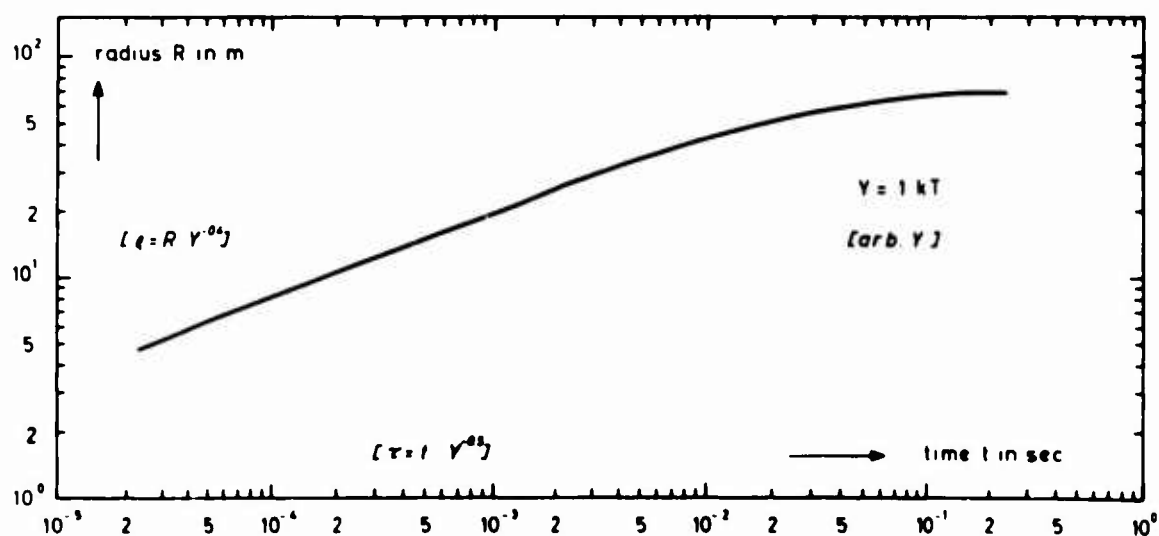
Fig. 4 The assumed growth curve for the fireball after a 1 kT explosio·. The same curve holds for other explosive yields Y if we read $\tau = t . Y^{-0.5}$ instead of t along the abscissa and $\rho = R . Y^{-0.4}$ instead of R along the ordinate
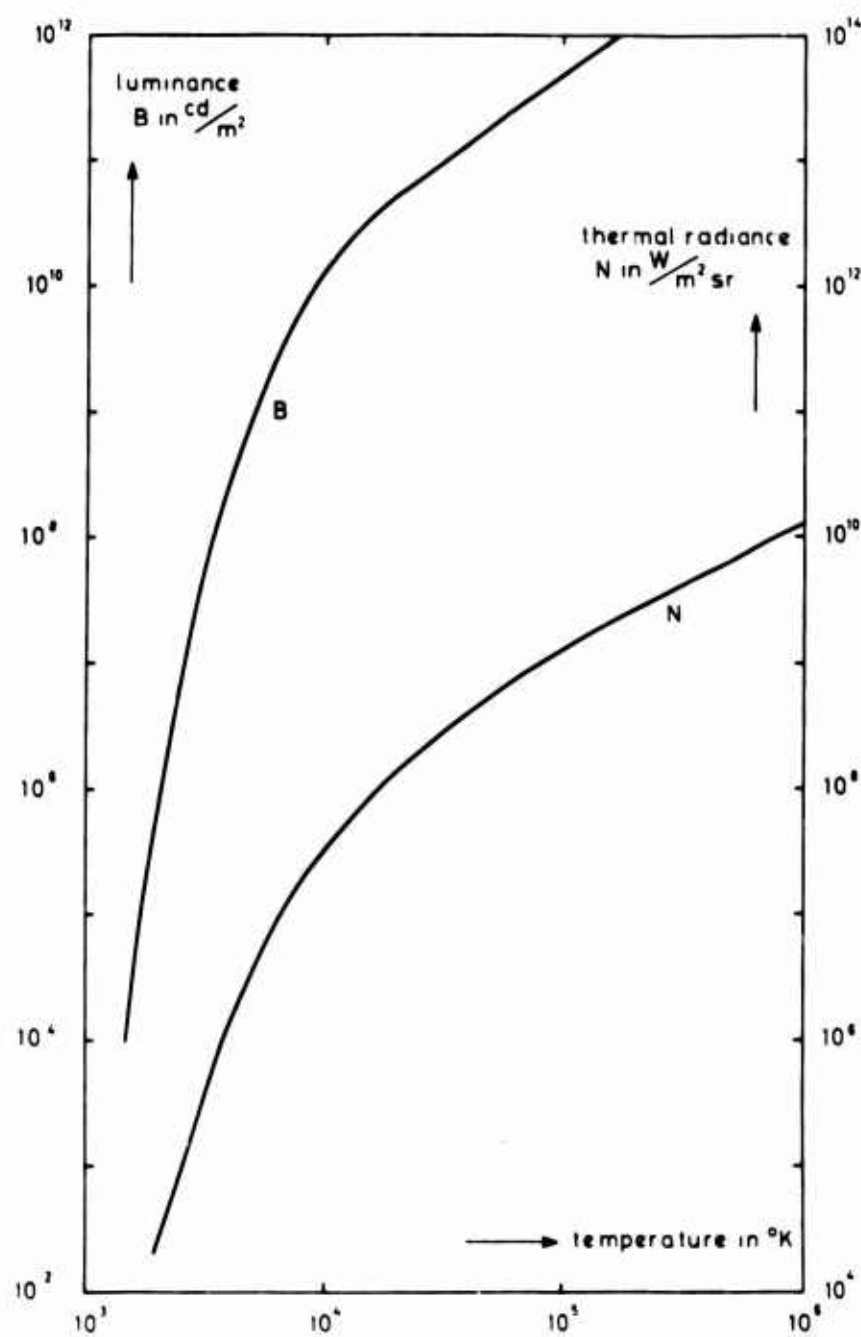
Fig. 5 The thermal radiance N and the luminance B of a black body as a function
of the temperature T
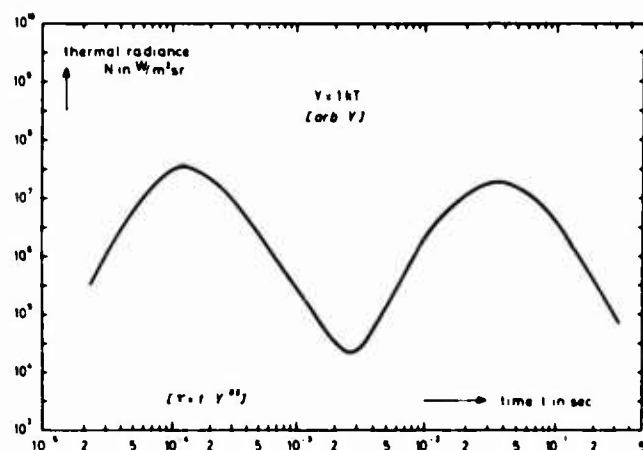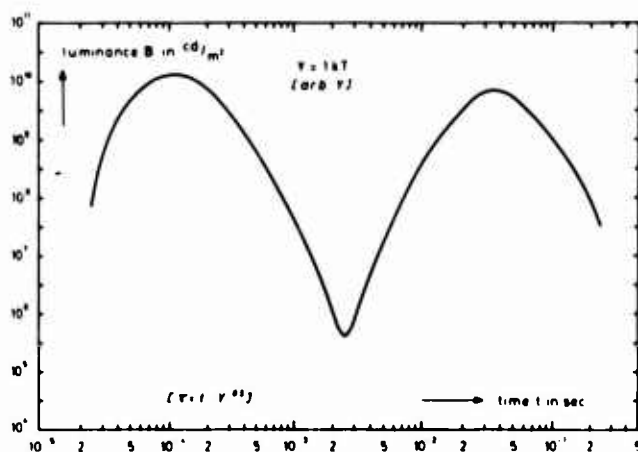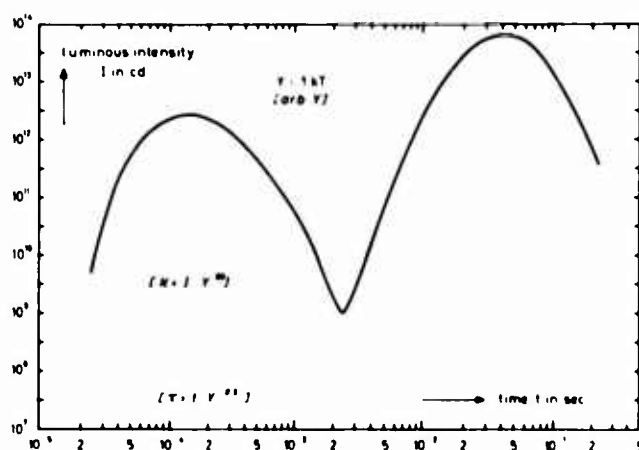
Fig.6(a),(b),(c)   The thermal radiance N   (a), the luminance B   (b), and the
                luminous intensity I   (c) of the fireball after a 1 kT
                explosion. The same graphs hold for other explosive
                yields Y   if we read the axes in generalized units as
                indicated between brackets
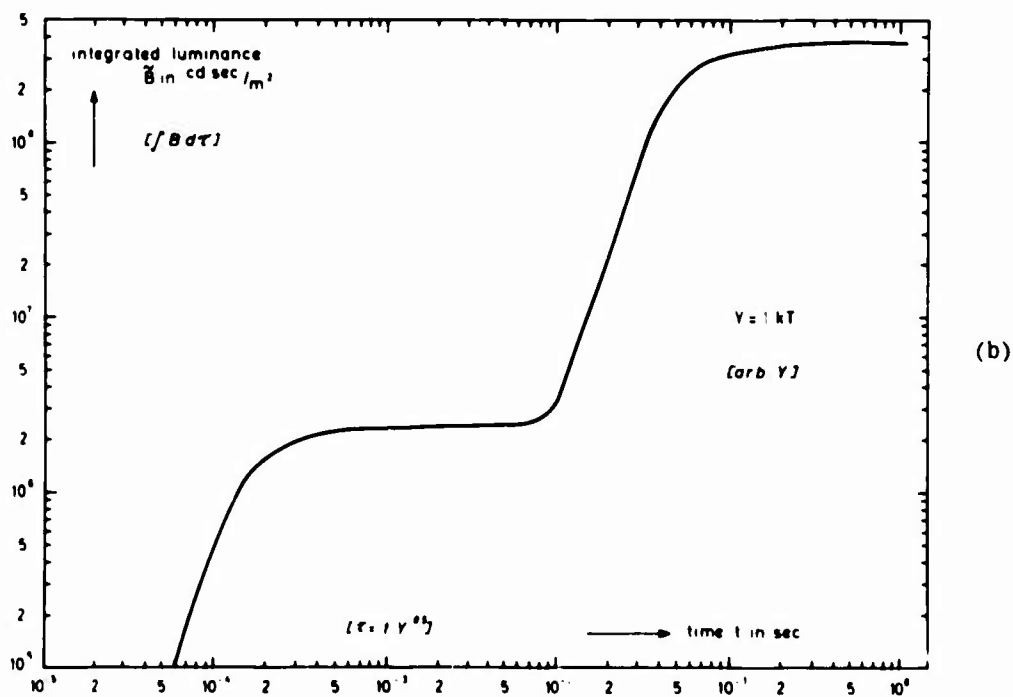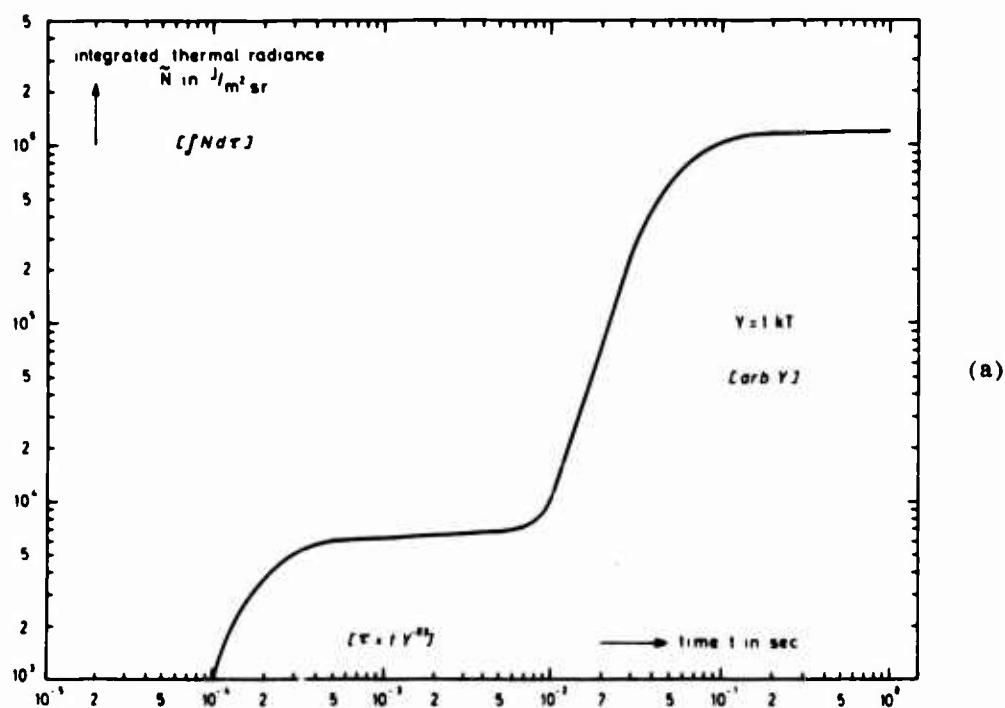
Fig.7(a),(b)   The cumulative thermal radiance Ñ   (a), and luminance B̃ (b) of the
fireball after a 1 kT explosion.   The same graph holds for other
explosive yields Y   if we read axes in generalized units as
indicated between brackets
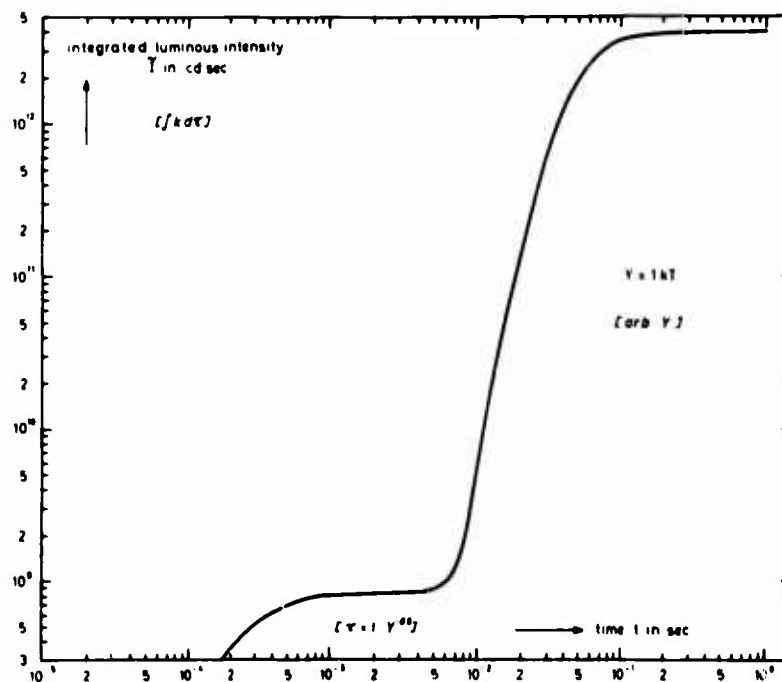
Fig.7(c)   The cumulative luminous intensity $\widetilde{Y}$ of the fireball after a 1 kT
explosion. The same graph holds for other explosive yields Y if
we read axes in generalized units as indicated between brackets
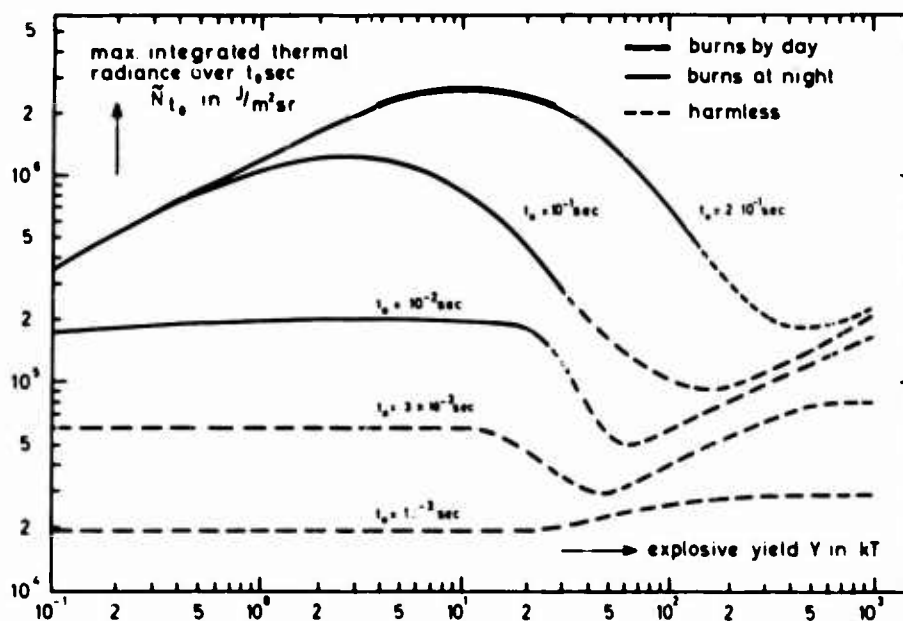
Fig.8(a)   The cumulative thermal radiance $\widehat{N}$ as function of the explosive yield Y
for various accumulation times (parameters). The curves are drawn in
full line when the level is above the critical level for retinal burn.
For the discussion see Section 5

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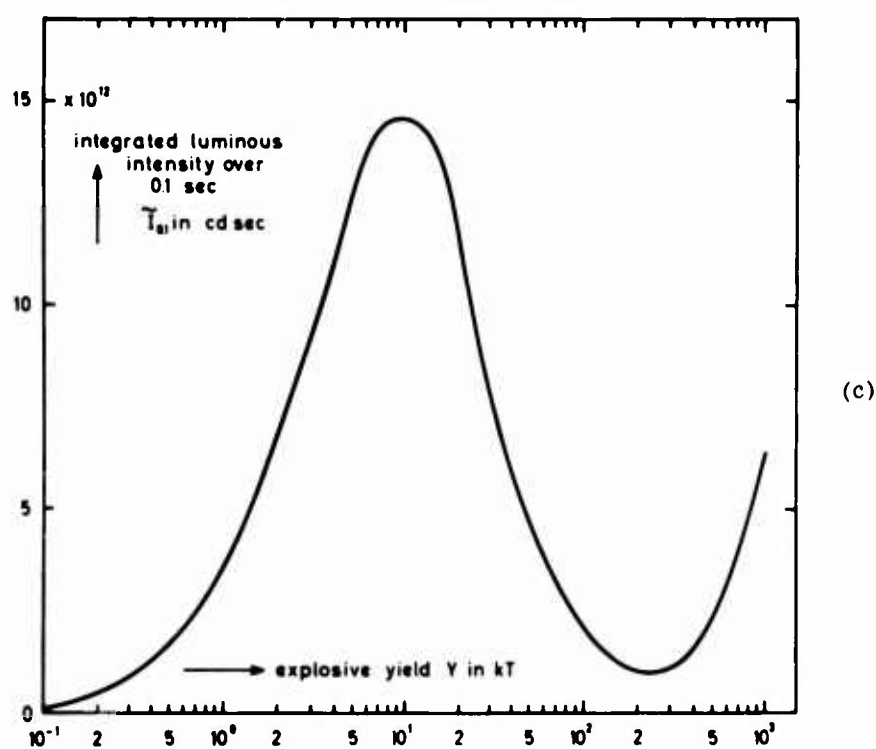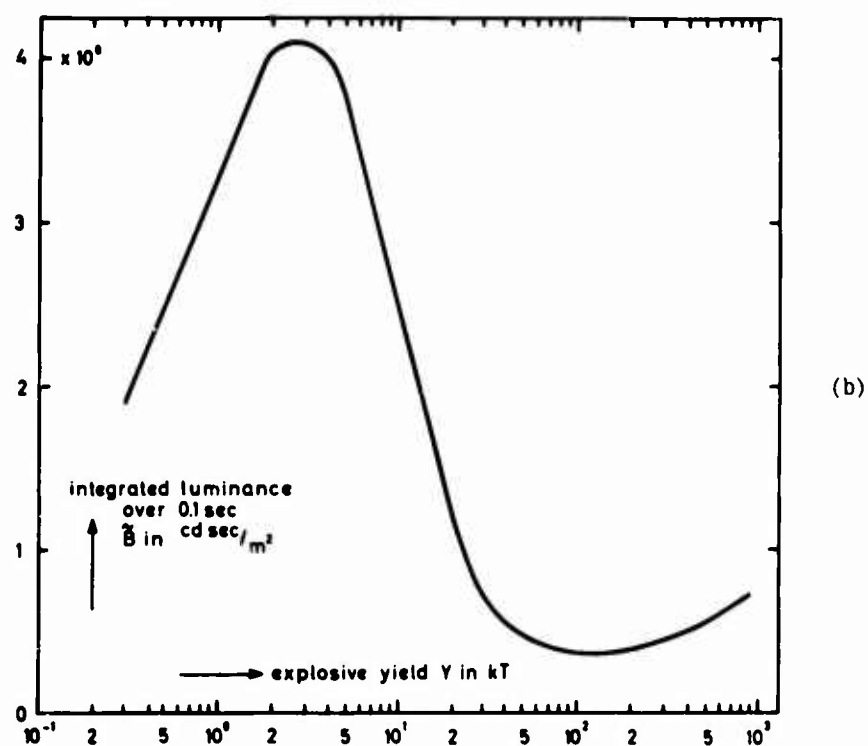
Fig.8(b),(c)   The over 0.1 sec integrated luminance $\tilde{B}$ (b) and luminous
intensity $\tilde{I}$ (c) as a function of the explosive yield Y
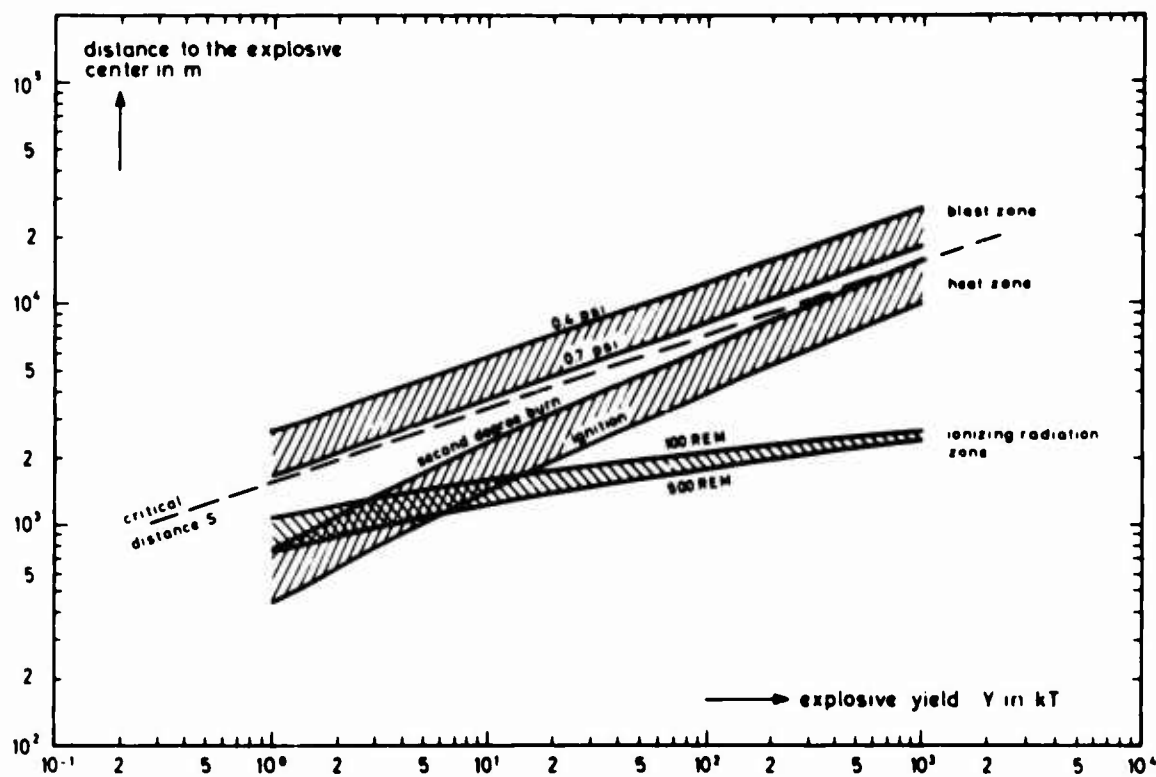
Fig.9   The relation between damage and distance for three effects of nuclear
explosions. The interrupted line represents the critical distance
versus explosive yield relation at which survival becomes
questionable
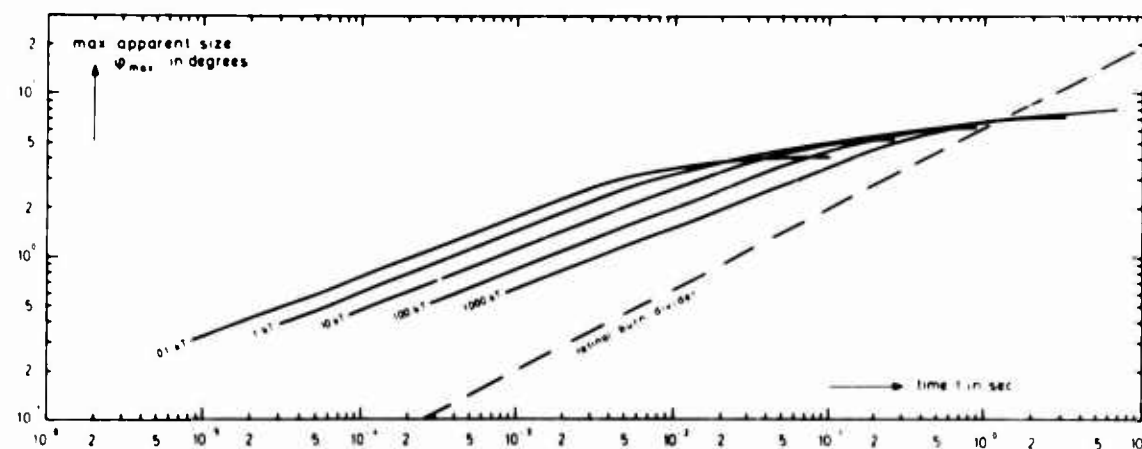
Fig.10   The maximum apparent size of the fireball after a nuclear explosion for a
surviving pilot. Parameter is the explosive yield Y . The interrupted
line indicates the minimum size which can be considered as infinitely
large from a heat technical point of view (see Section 5)
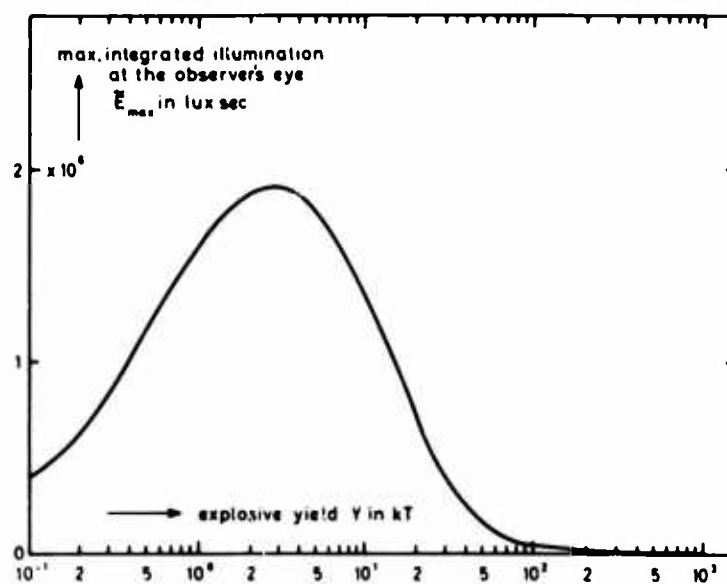
Fig. 11   The maximum cumulative illumination $\widetilde{E}_{max}$, produced at the minimum safe
distance S .   As indirect flash blindness is related to $\widetilde{E}$, weapons
around 3 kT explosive yield produce strongest indirect flash blindness
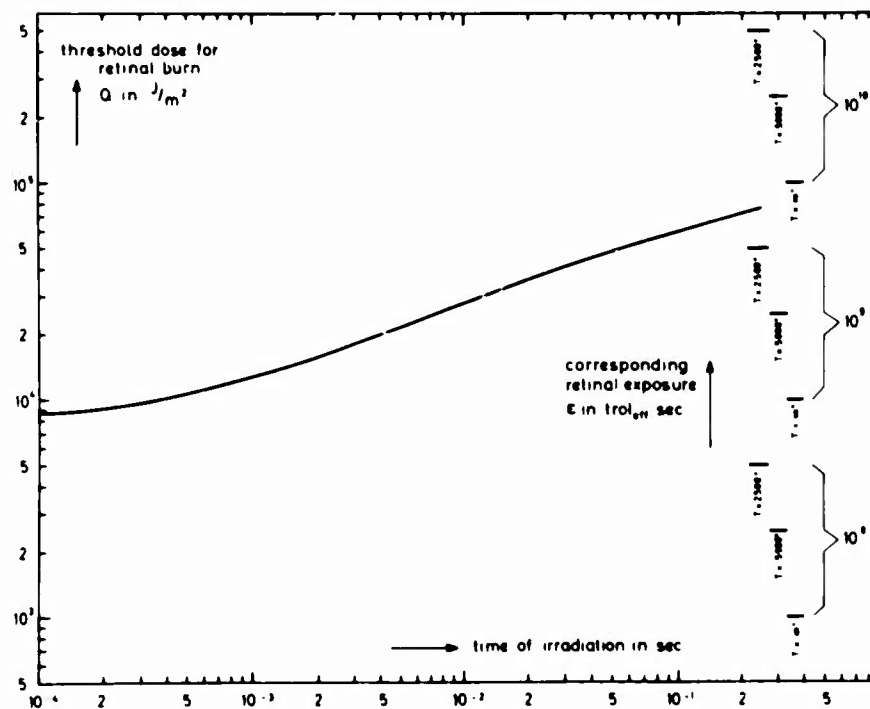

Fig. 12   The retinal dose   Q   which just produces retinal burn, as a function of the
time of irradiation.   Data according to Ham *et al*[10].   The scales to the
right indicate computed values of the retinal exposure for various
radiation temperatures
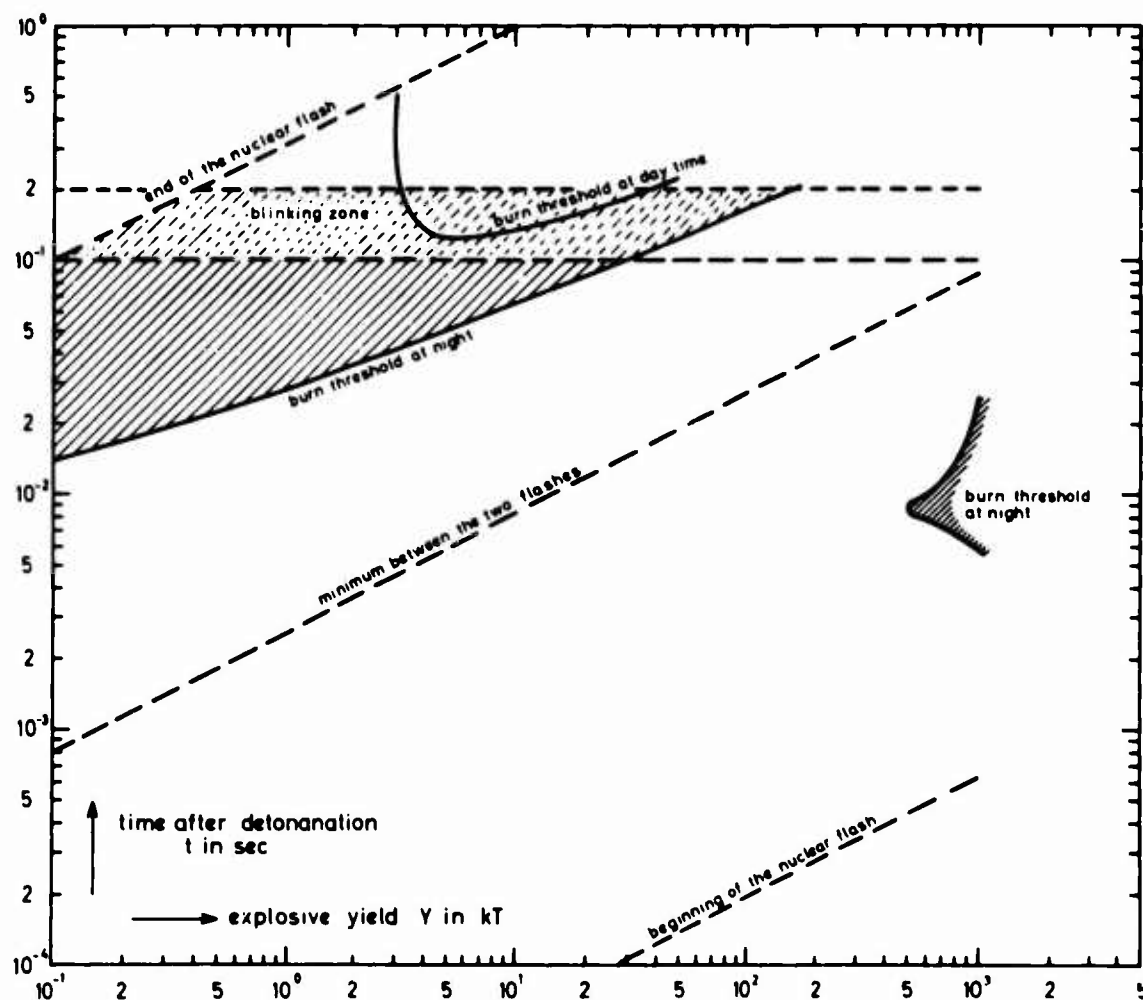
Fig.13   A survey of the temporal sequence of events in the production of retinal burn for various explosive yields. For details see text
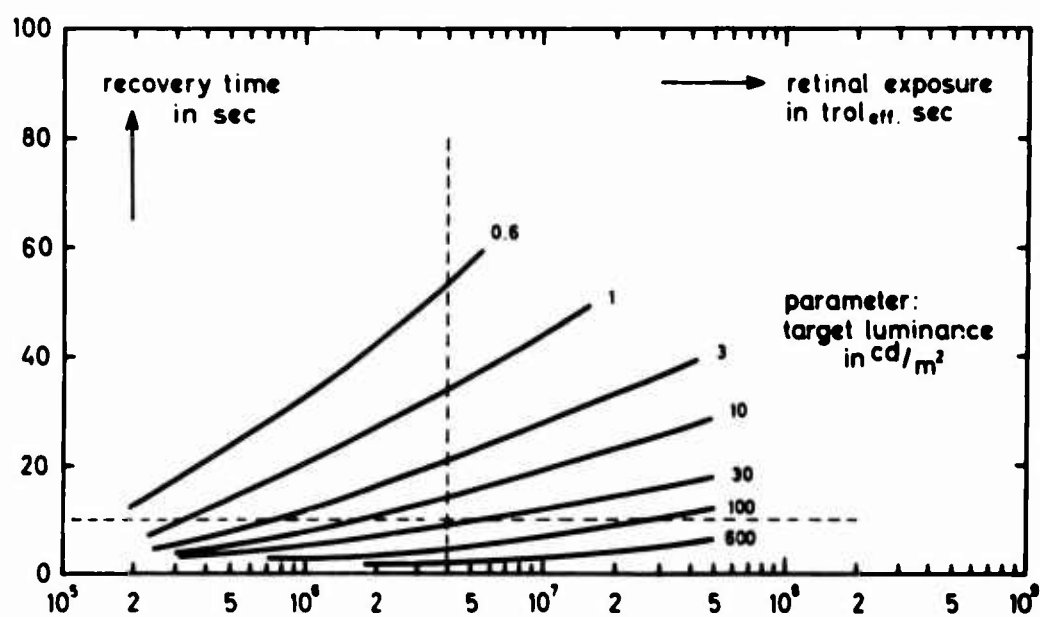
Fig. 14   Schematical indication of the dependency of the reading recovery time on the
flash exposure, based on critical evaluation of literature
data[11,12,13,14,15]. The interrupted lines together fence in the "working
area" of expectable flash exposure and admissable recovery times
(Sections 8 and 9)

PREDICTION OF EYE SAFE SEPARATION DISTANCES

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SUMMARY

A method is given for predicting the distances at which the thermal
radiation from nuclear detonations will be hazardous to the unprotected
human eye. This method relates calculated retinal exposure to experi-
mentally determined eye effects data. Graphs are used to show experimental
laboratory data relating minimal retinal burns and flash blindness
duration to retinal exposures. The laboratory data on minimal burns were
obtained using animals as the experimental subjects.

Eye hazards as a function of distance are determined for the unprotected
human eye exposed to sea-level, air-burst detonations from 0.01 to
1,000 kT yield. The pupil diameter of the human eye is taken to be 2.5 mm
and 6.0 mm, respectively, for day and night conditions and the effective
focal length of the eye is taken to be 17 mm.

Eye hazards as a function of distance are also determined for the human
eye protected by a 2% transmission fixed filter from daytime detonations.
The results indicate that use of such a filter will provide eye protection
at distances where other hazards become limiting factors.

PREDICTION OF EYE SAFE SEPARATION DISTANCES

Everett O. Richey

INTRODUCTION

The basic physical problem in the prediction of retinal burns is the determination of the increase of temperature in the retinal region in which the fireball is imaged. Areas in which the temperature, or time at some critical temperature, exceeds a certain value may be presumed to be irreversibly damaged. However, the nature of the problems and the difficulties in measuring and relating temperature profiles to functional effects have led to an approach by which observed retinal effects are associated with calculated retinal exposures. This approach is based on laboratory investigations which have established the dependence of ophthalmoscopically observable effects on total retinal exposure, retinal irradiance, and image size. The curves in Figure 1 are based on the latest and most complete laboratory data available at this time[1].

A similar approach is used in estimating the duration of flash-blindness following exposure to a nuclear detonation. Calculated retinal exposures appropriate to the flash-blindness problem are related to laboratory investigations which have established the dependence of flash-blindness duration on retinal exposure, illumination of the visual target following exposure, and visual acuity necessary to perform the required task (Fig. 2)[2].

The use of these methods requires the calculation, from known source characteristics, of the retinal exposure, retinal irradiance, and image diameter associated with exposure to a nuclear detonation. The calculations are greatly simplified by using approximations of nuclear detonation characteristics.

CALCULATION OF RETINAL EXPOSURE

The retinal exposure resulting from viewing a nuclear detonation can be calculated if the exposure conditions are known. The effective radiant exposure, Q_r, of the retina may be expressed as

$$Q_r = \frac{10^{12} a p k W T_e T_a T_x}{4\pi f^2 D_{fb}^2} \text{ (cal/cm}^2) \quad .$$

(1)

The average retinal irradiance, H_r, is simply

$$H_r = \frac{Q_r}{t} \text{ (cal/cm}^2\text{-sec)}$$

(2)

and the image diameter, D_i , is given by

$$D_i = \frac{FD_{fb}}{D} \text{ (mm)} \tag{3}$$

where a = 0.8 = fraction of the thermal energy radiated which is located in the spectral region effective in producing retinal damage ($350 \text{ m}\mu < E\lambda < 1500 \text{ m}\mu$ assuming a 5800°K black-body radiator)

   p = 1/3 = fraction of total weapon yield converted to thermal energy (low-altitude detonations)

   k = fraction of thermal energy released during time t

   W = yield of the weapon in kilotons

T_e = 0.8 = average transmission of clear media of the eye (assumed 5800° black-body spectrum)[3]

   T_a = average transmission of the atmosphere

   T_x = average transmission of any material between the eye and the detonation (i.e., aircraft canopy, sun glasses, filters)

   $f = \dfrac{F}{D_p}$ = ratio of the effective focal length of the eye-lens system to the diameter of the pupil

   D_{fb} = average fireball diameter in centimeters during exposure time t

   t = exposure time in seconds

   D = distance to fireball in centimeters.

Retinal exposures have been calculated, utilizing this method, for human eyes exposed to sea-level air-burst detonations from 0.01 kT to 10 kT, under both day and night conditions. In these calculations the effective focal length, F , and the bright daylight pupil diameter, D_p , of the human eye are taken to be 17 mm and 2.5 mm, respectively, resulting in a value of f = 6.8 . The night-time pupil diameter is taken to be 6 mm, resulting in a value of f = 2.83 , based on a recent investigation by Alder[4] in which he reports the average pupil diameter under dim cockpit conditions to be 5.9 mm.

The radiant power of a nuclear detonation is less than 45% of the maximum radiant power after an elapsed time of $2t_{max}$, and, along with the apparent surface temperature of the fireball, continues to decrease rapidly. Thus, the energy effective in producing eye hazards is assumed to be radiated in a time $t = 2t_{max} = 0.064 \ W^{0.5}$sec. This is assumed to be less than the blink reflex time for the yields considered here. During this period of time the fireball emits approximately 47% of the total energy radiated; thus, we have k = 0.47 . The assumed average fireball diameter is that corresponding to t_{max} or $D_{fb} = 9.33 \times 10^3 W^{0.4}$cm. (Nuclear detonation characteristics are all from Reference 5.)

Substituting the values above in Equations (1), (2) and (3) gives the quantities listed in Table I, which require only appropriate values for D , T_a , and T_x for the determination of D_i , Q_r , and H_r .

Atmospheric transmission was calculated using the equation $T_a = ex\cdot(-\kappa D)$, where D is the distance in km and κ is an average extinction coefficient dependent on visibility. Transmission values were determined for three different conditions of visibility· 20 km ($\kappa = 0.20$ km^{-1}); 40 km ($\kappa = 0.10$ km^{-1}); and 80 km ($\kappa = 0.03$ km^{-1}) (Ref.5).

DISCUSSION

Retinal Burns

Image diameter, retinal exposure, and retinal irradiance were calculated for both day and night exposure conditions for each of the yields listed in Table I, for each of the assumed visibilities, and for values of $T_x = 1$ (no intervening filters) and $T_x = 0.02$ (2% transmission fixed filter).

Figure 3 is a plot of retinal exposure and image diameter versus distance for daytime exposure to a 0.01 kT detonation for visibilities of 20, 40 and 80 km with no filter and with a 2% fixed filter. Also shown in Figure 3 is a plot of the threshold retinal exposure, Q_r^t , required to produce a minimal retinal burn. Q_r^t for each distance was determined by using the exposure time and image diameter in conjunction with the threshold curves in Figure 1. The distance at which Q_r^t exceeds the retinal exposure, Q_r , is the predicted threshold distance for minimal retinal burns. Figure 4 is a plot of the same informatic· for night-time exposure to a 0.01 kT detonation and Figures 5 and 6 are similar plots for a 10 kT detonation.

This method was used to determine the threshold distance under both day and night exposure conditions and each assumed visibility for each yield listed in Table I. Figure 7 is a plot of the threshold distance versus yield for the day exposures and Figure 8 is a similar plot for the night exposures.

The threshold distance for a bright daylight exposure with clear air (80 km visibility) varies from about 1.3 to 11 km as the detonation yield varies from 0.01 to 10 kT. However, when the visibility is limited (20 km), the threshold varies from about 1.1 to 4.6 km for the same range of yields. Comparable distances for night exposures vary from 3.8 to 26 km for clear air and 3.0 to 10.5 km with limited visibility.

The use of a fixed filter with 2% transmission results in retinal exposures well below burn threshold values for each of the yields considered, as shown in Figures 3, 4, 5, and 6. During daylight hours such a filter reduces the retinal exposure more than an order of magnitude below the threshold exposure. For night-time conditions the retinal exposure is reduced by a factor of approximately 2.5 below the threshold exposure.

The threshold distances reported here are based on the assumption that the absorption properties of the human retina are essentially the same as those for a rabbit – as suggested by the absorption measurements of Geeraets *et al'*. In addition, the curves in Figure 1 show the thermal exposure which will produce a minimal burn, defined as a very slight coagulation of the retinal tissue which becomes ophthalmo-scopically visible between 3 and 5 minutes after exposure[1,3,7]. The exposure required

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to produce permanent damage is undoubtedly less than that required to produce burns defined in this way. However, there is as yet no satisfactory definition of minimum acceptable damage.

The threshold exposures curves in Figure 1 are conservative in one respect, however. The energy spectrum of the source used in obtaining the data on which these curves are based was deficient in the infrared relative to a $5800^{\circ}K$ black-body radiator (Fig. 9). Since the retina does not appear to absorb energy in the infrared as effectively as energy in the visible region of the spectrum[6], the threshold curves of Figure 1 are somewhat lower than would be expected for a $5800^{\circ}K$ black-body source – a source that in some respects resembles some nuclear detonations.

The predicted distances for minimal burns shown in Figures 7 and 8 obviously cannot be interpreted as the distances at which humans may safely view nuclear detonations without eye protection. A safety factor needs to be introduced. However, the amount of this factor and how it should be introduced have not yet been arbitrated. One possibility is simply to lower the threshold curves for minimal burns by some arbitrary factor generally suggested to be between 5 and 10. Once this factor is selected, it is only necessary to shift the ordinate scale of Figure 1 to determine "safe" separation distances.

An increase in detonation altitude with the consequent increase in fireball diameter, energy emission rate, and atmospheric transmission[5] results in threshold distances greater than those shown here. The reader is cautioned against using these curves for other than sea-level air-burst conditions and for yields beyond the range spanned by these calculations. The basic method of calculation can be used for different detonation altitudes and other yields, but it may be necessary to consider different detonation characteristics for these conditions.

Flash-blindness

The problem of attempting to predict the flash-blindness caused by a nuclear detonation is complicated by a large number of variables with an almost infinite range of variations. Even when the range of possible detonation yields and altitudes is restricted to those considered here (0.01 to 10 kT sea-level air-burst detonations), different possibilities of cloud cover, position of the fireball in the field of view, light-scattering haze, etc., are innumerable.

The approach taken here assumes the worst case, i.e., direct (foveal) viewing of the fireball, and, by relating calculated exposures to laboratory data, determines the distances from the fireball at which recovery times of 5 sec or less are predicted. Laboratory data indicate that a retinal exposure of 0.01 cal/cm^2 will result in a recovery time of approximately 5 sec for a brightly lighted visual task (Fig. 2). Retinal exposures for a variety of yields and exposure conditions were calculated earlier in the determinations of the retinal burn hazard (Figs. 3, 4, 5, 6). These calculated exposures were used to determine the predicted distances for a retinal exposure of 0.01 cal/cm^2 for 0.01 to 10 kT detonations in bright daylight for the human eye protected by a 2% fixed filter. The results are shown in Figure 10.

The predicted distance for a retinal exposure of 0.01 cal/cm^2 in clear air (80 km visibility) varies from about 15 to 62 km as the detonation yield varies from

0.01 to 10 kT. However, when the visibility is limited (20 km) this predicted distance varies from about 2 to 9 km for the same range of yields.

The recovery times shown in Figure 2, however, are the times required by a subject to identify a 28.4 minute test letter (visual acuity 0.176) while looking through the afterimage caused by a bright flash of light subtending a visual angle of 10° and centered on the fovea[2]. No attempt was made to determine the subject's ability to identify the test letter by using peripheral vision and "looking around" the after-image. Weymouth et al[8], however, report that the visual acuity 5° off the fovea is about 0.30, which certainly should be sufficient to identify a test letter requiring a visual acuity of only 0.176.

The author has personally viewed a standard altimeter at a distance of 76 cm (30 inches) – average eye-to-instrument distance in fighter aircraft – following exposure to centrally fixated flashes of bright light. No difficulty was experienced in reading the altimeter when the afterimages subtended visual angles of 3° or less, even though individual numbers, when fixated directly, could not be identified through the afterimages. As the visual angle subtended by the afterimages increased from 3°, the altimeter became increasingly difficult to read until, at 10°, a great deal of concentration and repeated peripheral scanning were required to determine the altitude to the nearest 100 feet. A pilot, however, cannot concentrate on a single instrument to the exclusion of all else.

Thus, rather arbitrarily, a centrally located afterimage subtending a visual angle of at least 3° was chosen as the condition necessary for a significant reduction in a pilot's ability to read his major flight instruments. An object which subtends a visual angle of 3°, however, produces a retinal image with a diameter of 0.9 mm. Therefore the pilot's ability to read his instruments should not be significantly affected by flash-blindness when the afterimage has a diameter of less than 0.9 mm. The pilot probably would be able to maintain some control of his aircraft with after-images greater than this by peripheral reference to the horizon. The distance from a nuclear detonation at which a fireball image diameter of 0.9 mm would be produced varies from 0.28 to 4.5 km as the yield varies from 0.01 to 10 kT (Fig. 10).

To summarize briefly, a pilot viewing a small, daytime, low-altitude nuclear detonation through a 2% fixed filter would receive a retinal exposure of the order of 0.1 cal/cm^2 at the distances indicated in Figure 10. At these distances, however, the afterimages would be less than 0.9 mm and the pilot should be able to read his instruments without much difficulty. At distances less than those indicated by the 0.9 mm line in Figure 10, the pilot will experience increasing difficulty in reading his instruments but should be able to maintain some control of his aircraft unless he is close enough to be within the lethal envelope of other effects. At distances inside the 0.01 cal/cm^2 lines, the pilot, although able to control his aircraft, would not be able to perform a task requiring central visual acuity for at least 5 sec after exposure.

The curves in Figure 10 are applicable only under the conditions specified here. The retinal exposures from night detonations or day detonations without eye protection exceed the limits of laboratory data available at this time.

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CONCLUSIONS AND RECOMMENDATIONS

The threshold distances for minimal retinal burns reported here are recommended for use as a guide in establishing interim eye safety criteria. They are believed to be a reasonable and realistic assessment of the eyeburn hazard from small nuclear detonations. The method and technic used here have been used successfully in the past to predict experimentally verified threshold distances for animals, although not for the range of yields covered here. Additional work is needed, however, to (a) extend the threshold curves for minimal burns to primates to allow extrapolation to man with more confidence, (b) establish a realistic safety factor and a method of introducing it into the prediction technic used here, and (c) establish a definition of minimum acceptable damage.

Concerning the flash-blindness problem, it is recommended that the results reported here be used as an interim guide in establishing operational criteria. It is evident, however, that additional experimental work in this area is needed to (a) establish the relationship between retinal exposure and exposure time for various recovery endpoints, e.g., 5 sec to read an altimeter, (b) obtain recovery time data in the exposure area where safety considerations preclude the use of human subjects, and (c) establish the ability of trained pilots to control aircraft under various conditions of flash-blindness.

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TABLE I. Exposure time, image diameter, retinal exposure, and retinal irradiance as functions of yield, distance, atmospheric transmission and filter transmission. (Human eye exposed to sea-level air bursts.)

| W (kt)	t (sec.)	D_i (mm.)	Bright Daylight		Dim Cockpit	
			Q_r (cal/cm^2)	H_r (cal/cm^2-sec)	Q_r (cal/cm^2)	H_r (cal/cm^2-sec)
0.01	.0064	$\dfrac{2.50 \times 10^4}{D}$	$788 T_a T_x$	$123 T_a T_x$	$4.54 T_a T_x$	$709 T_a T_x$
0.03	.0111	$\dfrac{3.91 \times 10^4}{D}$	$.982 T_a T_x$	$88.5 T_a T_x$	$5.65 T_a T_x$	$510 T_a T_x$
0.1	.0202	$\dfrac{6.31 \times 10^4}{D}$	$1.25 T_a T_x$	$61.7 T_a T_x$	$7.19 T_a T_x$	$355 T_a T_x$
0.3	.0351	$\dfrac{9.81 \times 10^4}{D}$	$1.56 T_a T_x$	$44.3 T_a T_x$	$8.96 T_a T_x$	$255 T_a T_x$
1.0	.064	$\dfrac{1.59 \times 10^5}{D}$	$1.98 T_a T_x$	$30.9 T_a T_x$	$11.4 T_a T_x$	$178 T_a T_x$
3.0	.111	$\dfrac{2.46 \times 10^5}{D}$	$2.48 T_a T_x$	$22.2 T_a T_x$	$14.2 T_a T_x$	$128 T_a T_x$
10.0	.202	$\dfrac{3.98 \times 10^5}{D}$	$3.13 T_a T_x$	$15.4 T_a T_x$	$18.0 T_a T_x$	$89.0 T_a T_x$

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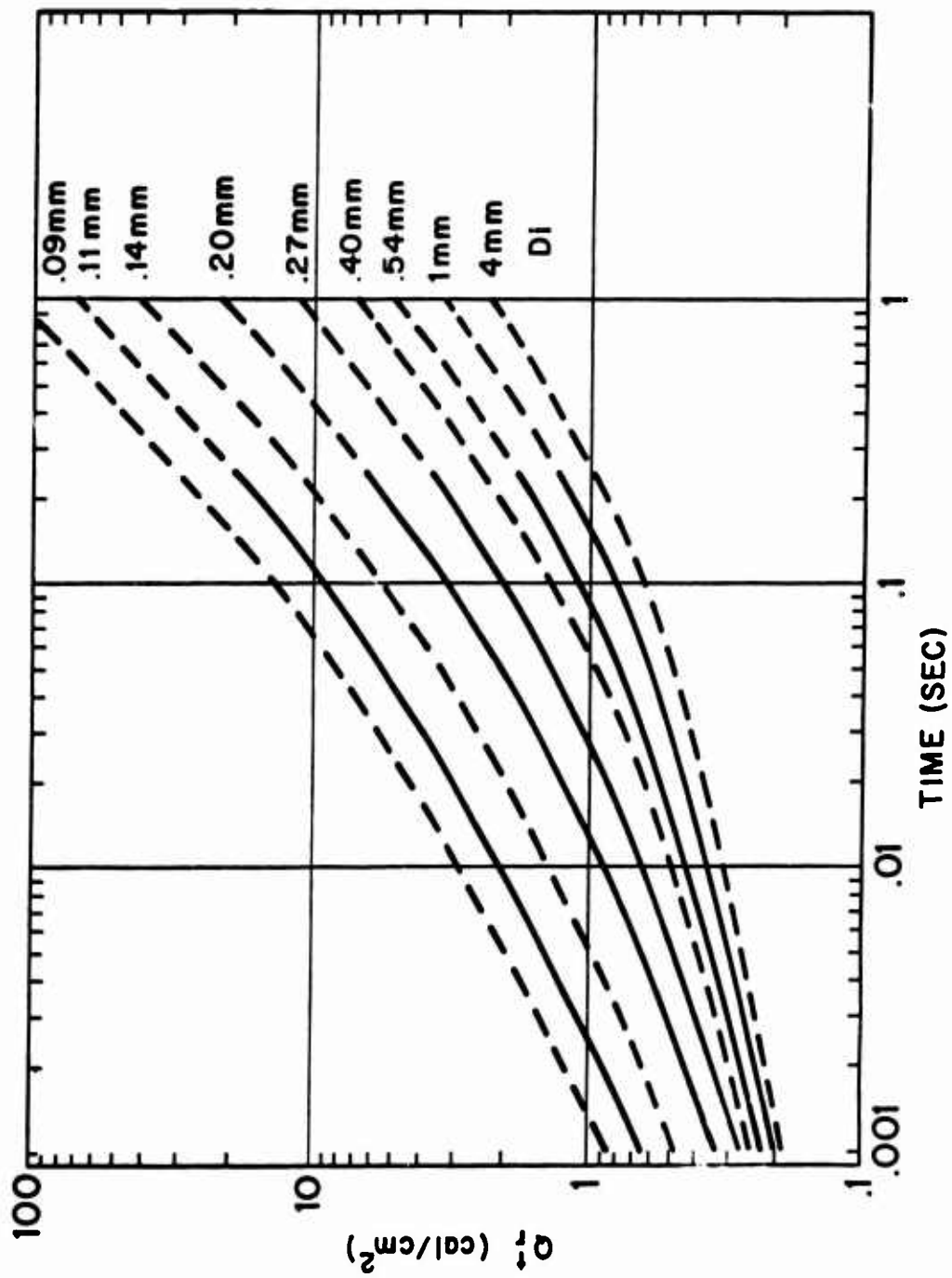
Fig. 1 Threshold retinal exposure, Q_r^t, versus time for the production of minimal
burns in the retina of pigmented rabbits
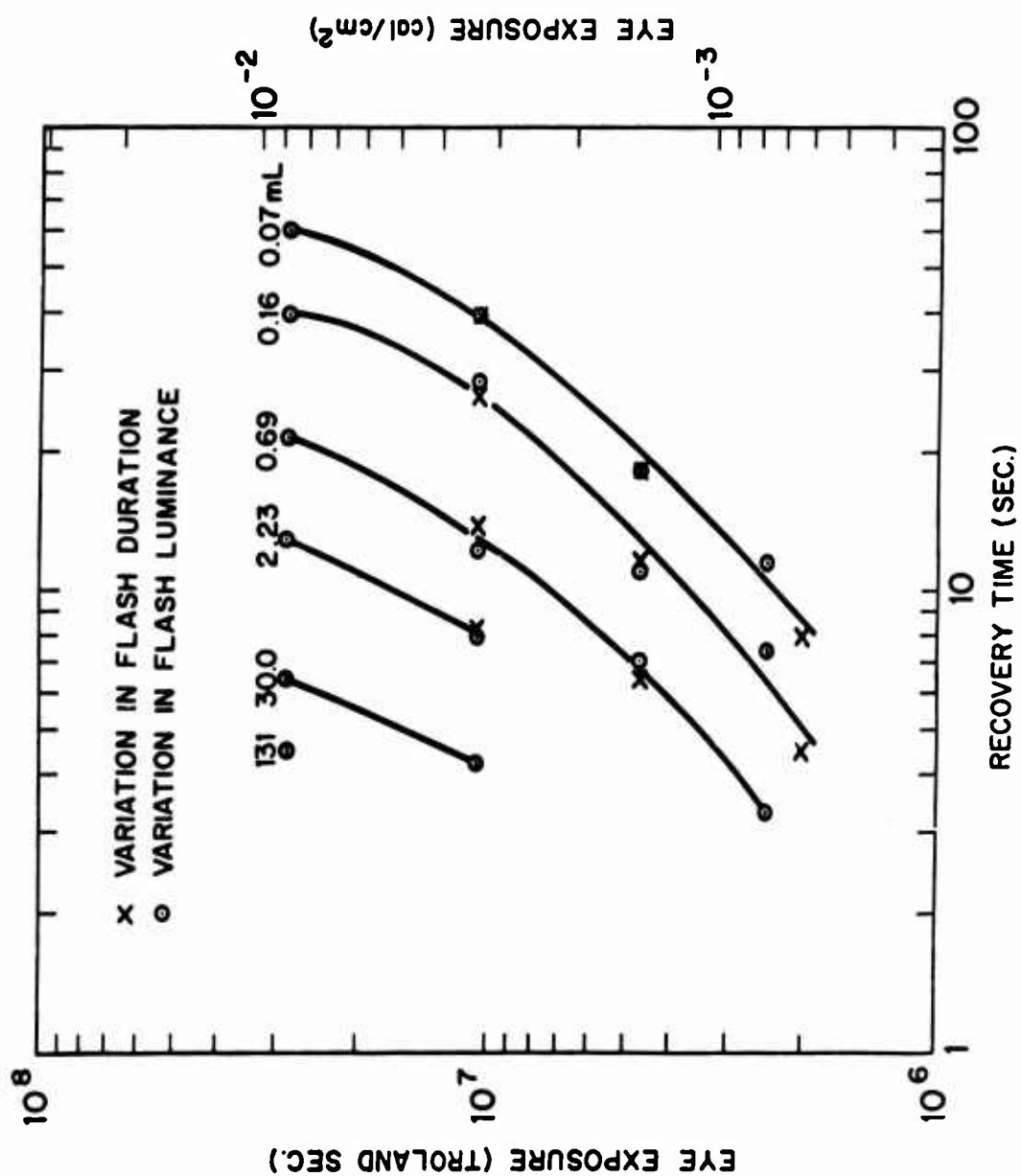(Dash lines are interpolated or extrapolated)

Fig. 2   Flash-blindness recovery time versus eye exposure for a 28.4 minute test
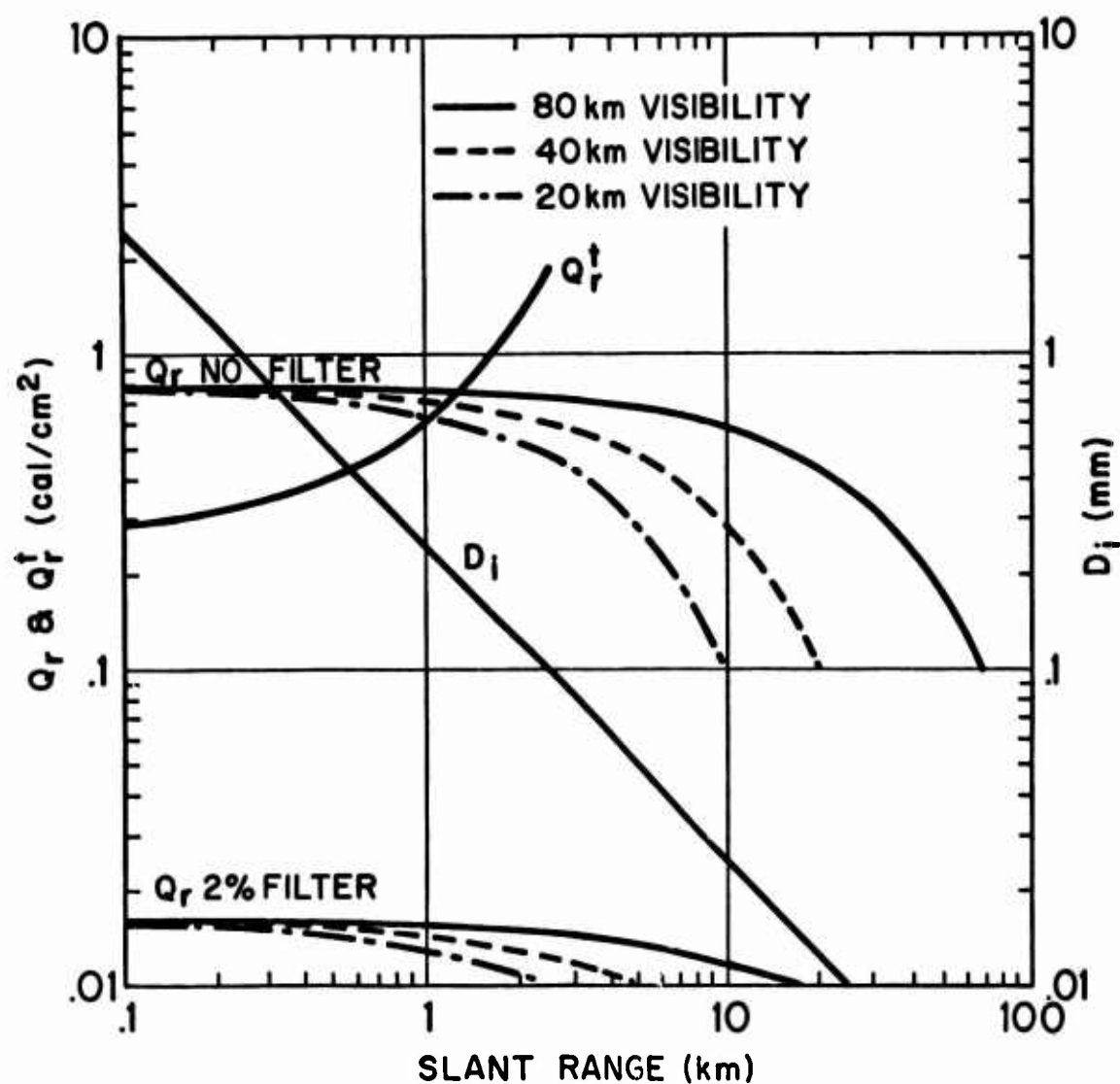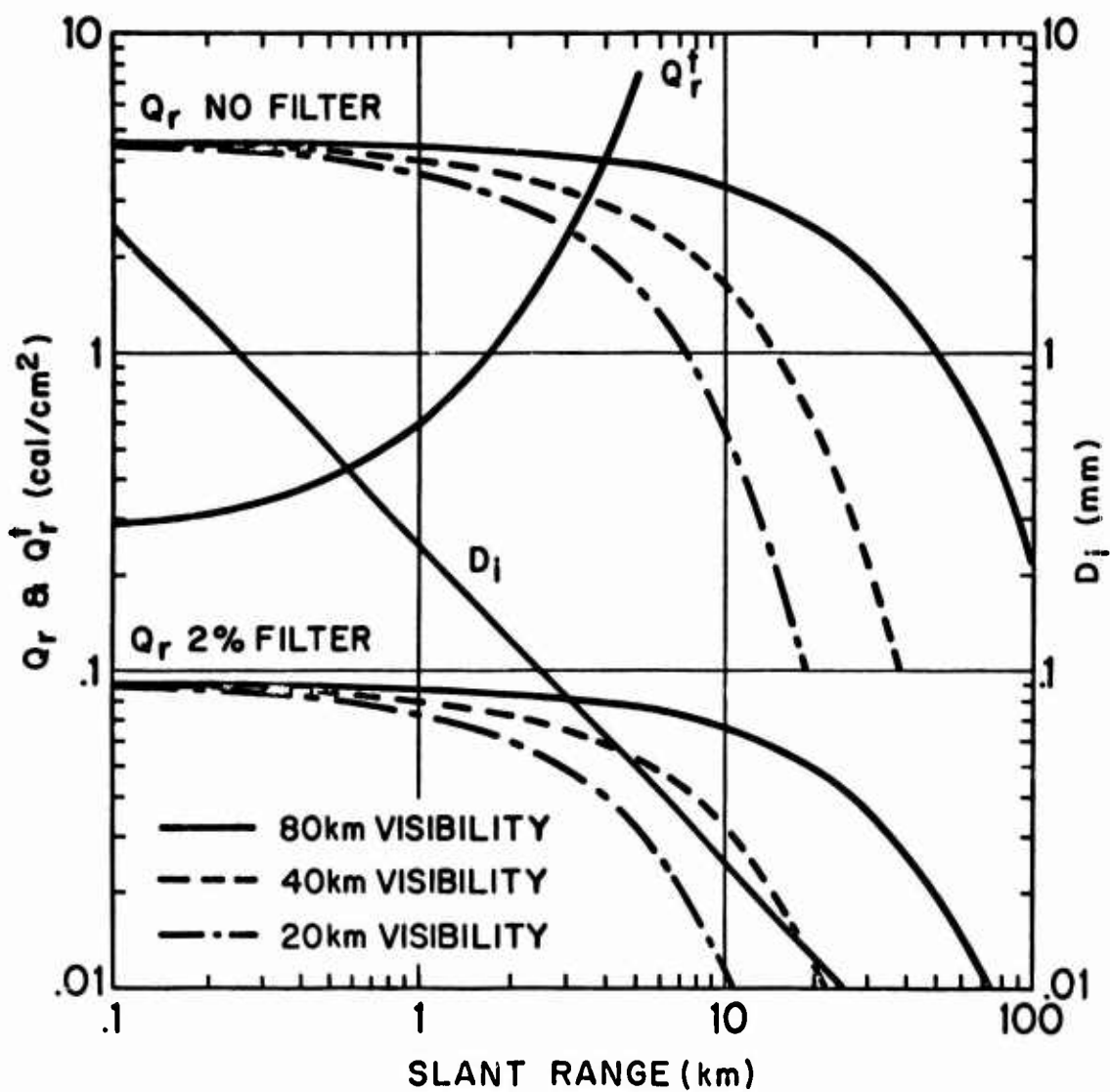letter presented at the indicated luminance levels
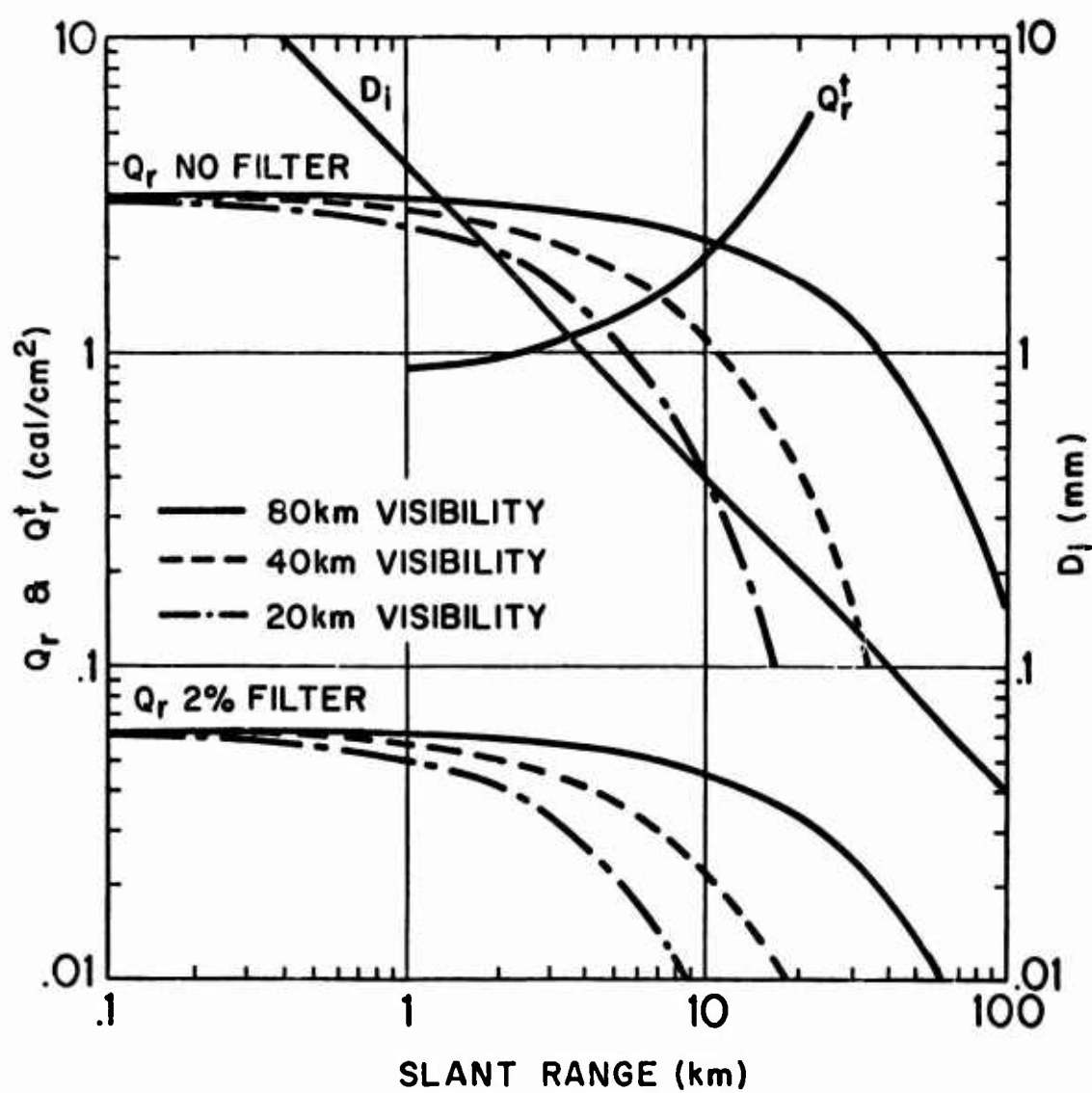
Fig.3   Image diameter, D_i, retinal exposure, Q_r, and threshold exposure, Q_r^t, as functions of distance from a 0.01 kT detonation for the human eye in bright daylight. Exposure time is 0.0064 sec
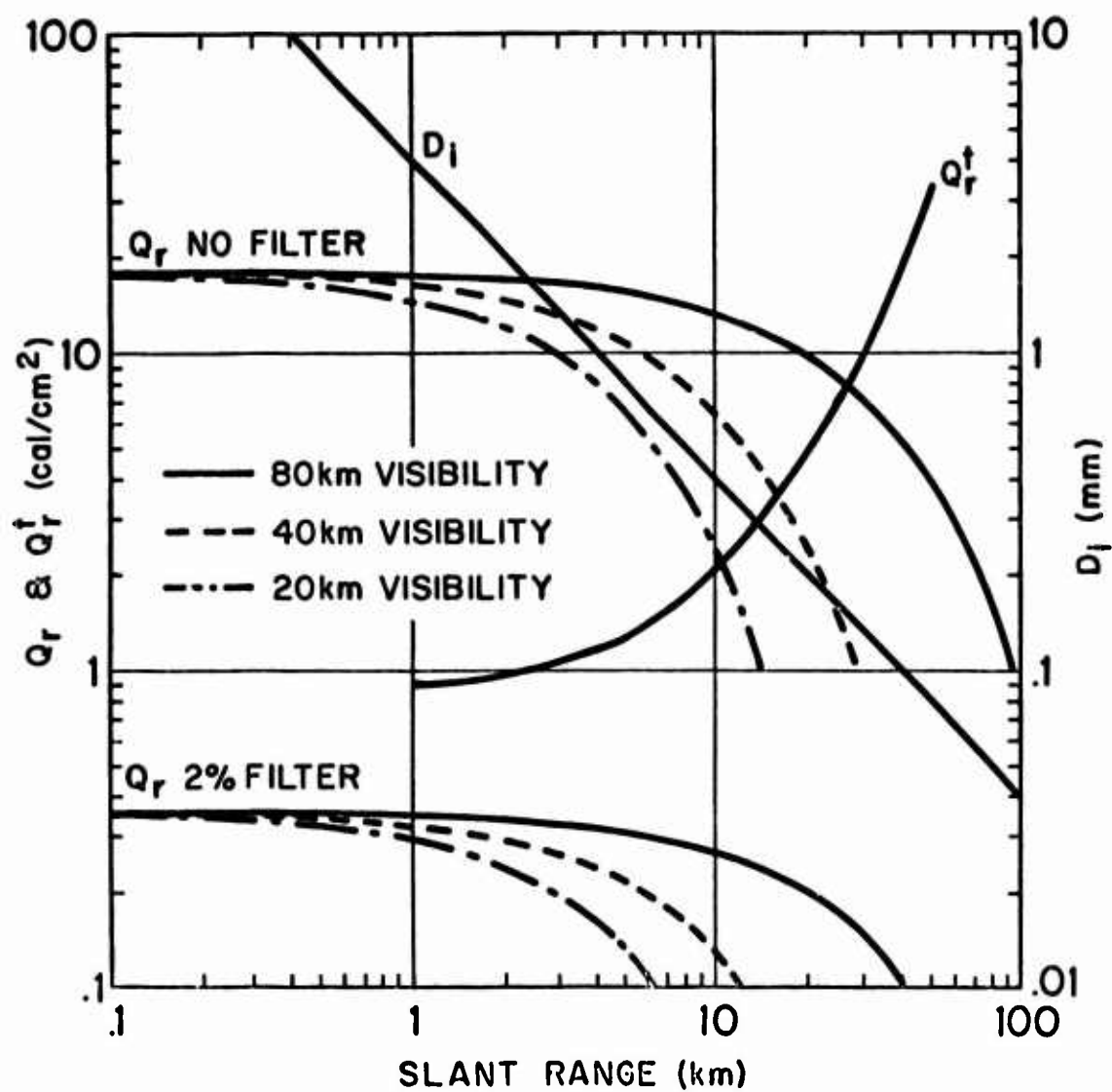
Fig. 4   Image diameter, D_i , retinal exposure, Q_r , and threshold exposure, Q_r^t , as functions of distance from a 0.01 kT detonation for the human eye at night.   Exposure time is 0.0064 sec

Fig. 5 Image diameter, D_i, retinal exposure, Q_r, and threshold exposure, Q_r^t, as functions of distance from a 10 kT detonation for the human eye in bright daylight. Exposure time is 0.202 sec

Fig.6   Image diameter, D_i, retinal exposure, Q_r, and threshold exposure, Q_r^t, as functions of distance from a 10 kT detonation for the human eye at night. Exposure time is 0.202 sec
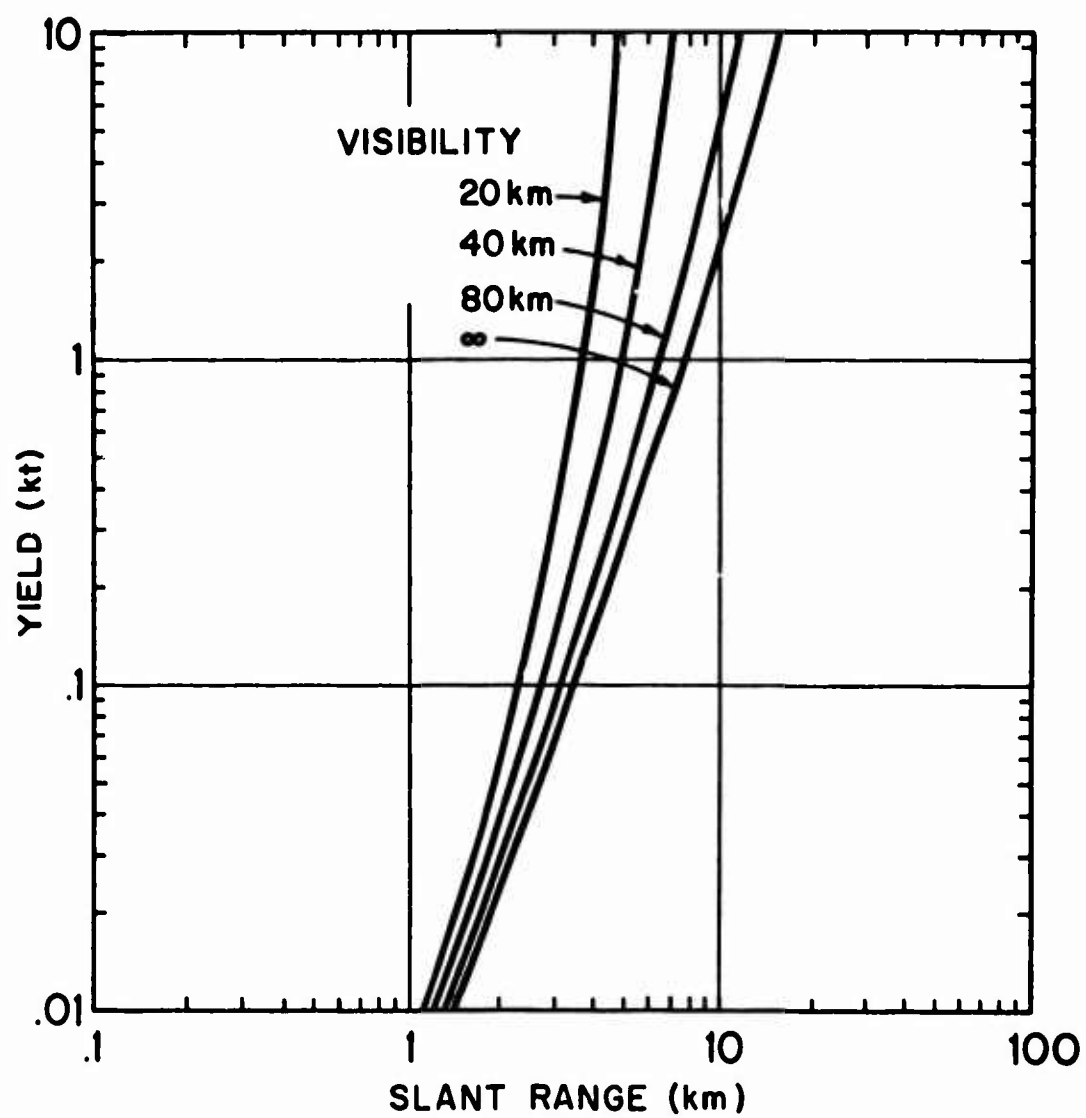
Fig.7   Threshold distance for minimal burn versus yield for human eye in bright
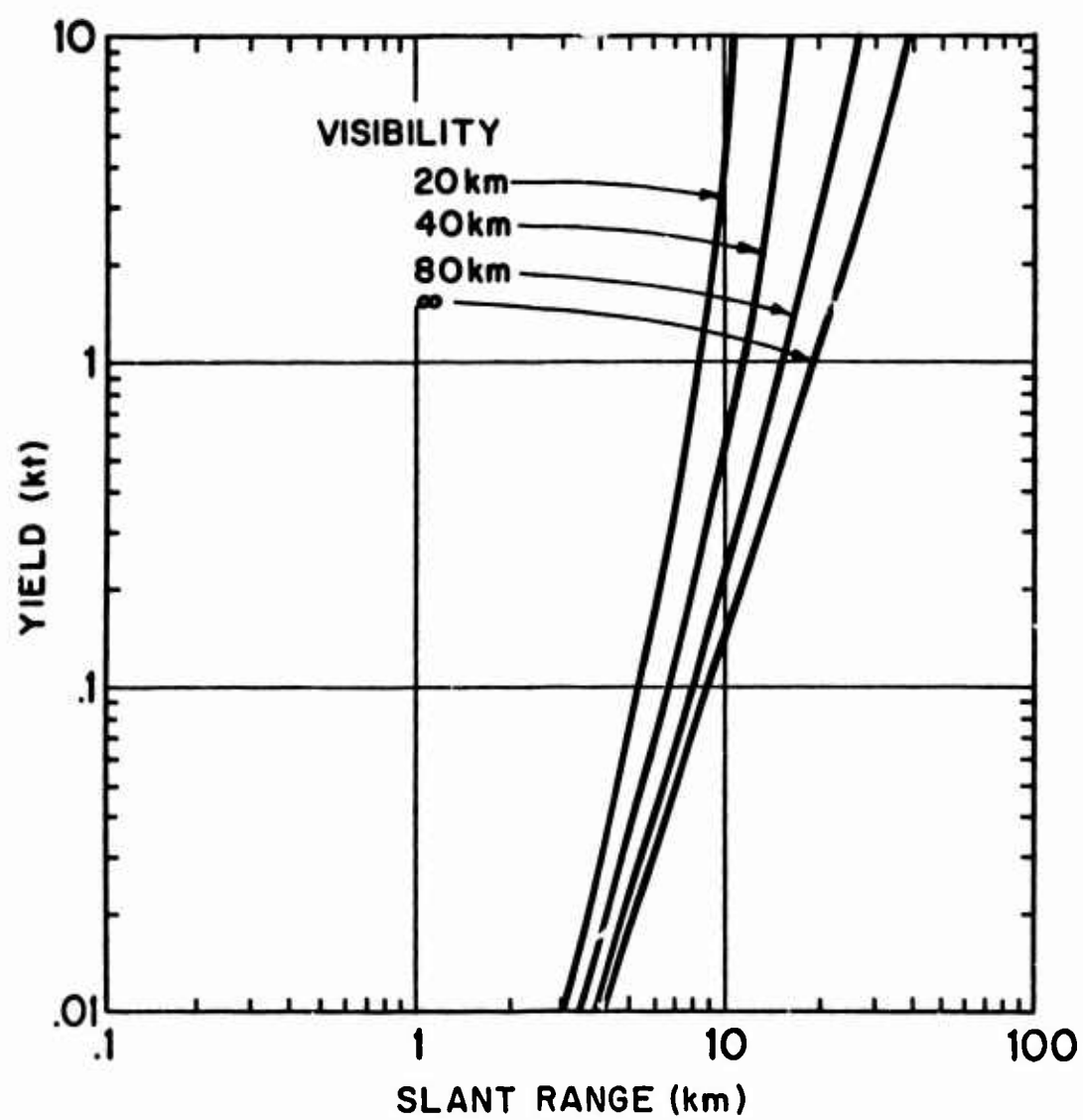davlight with no protection

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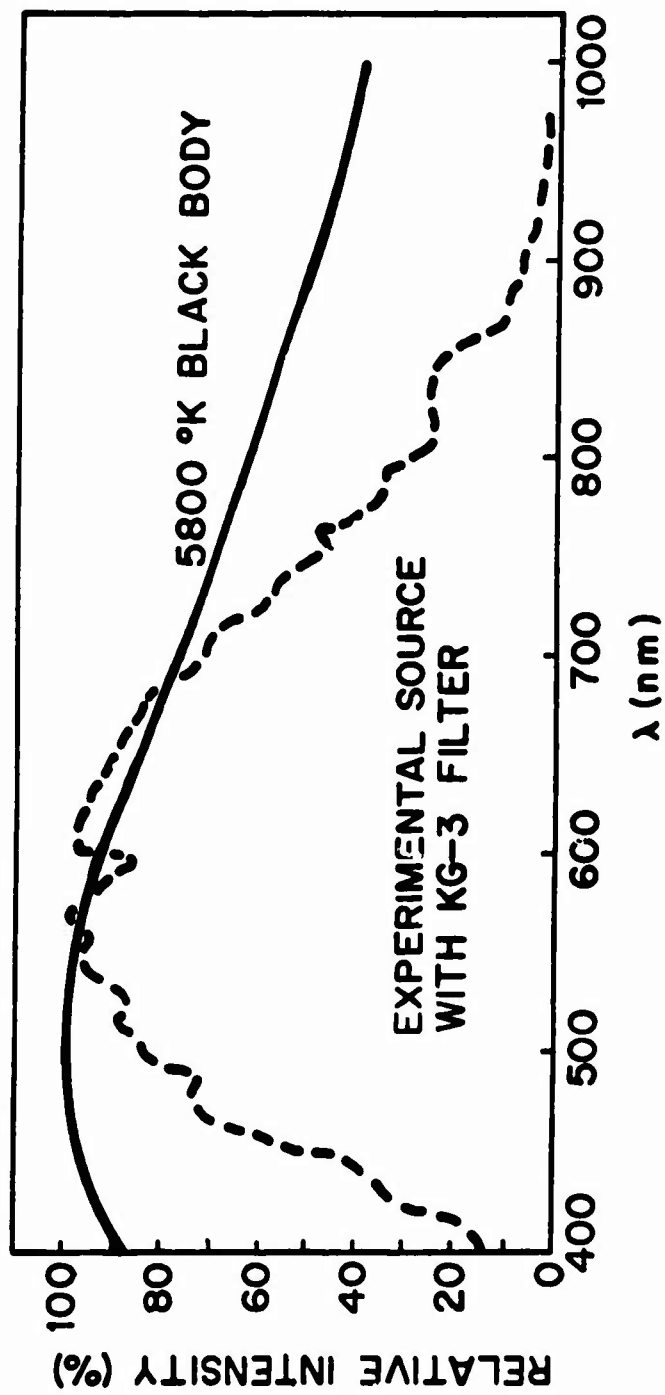Fig.8   Threshold distance for minimal burn versus yield for human eye at night with
no protection

Fig.9 Relative spectral distribution of the exposure source used in obtaining the threshold curves in Figure 1 compared to the relative spectral distribution of a 5800°K black-body radiator (nm = nano-meters = 10^{-9} meters)
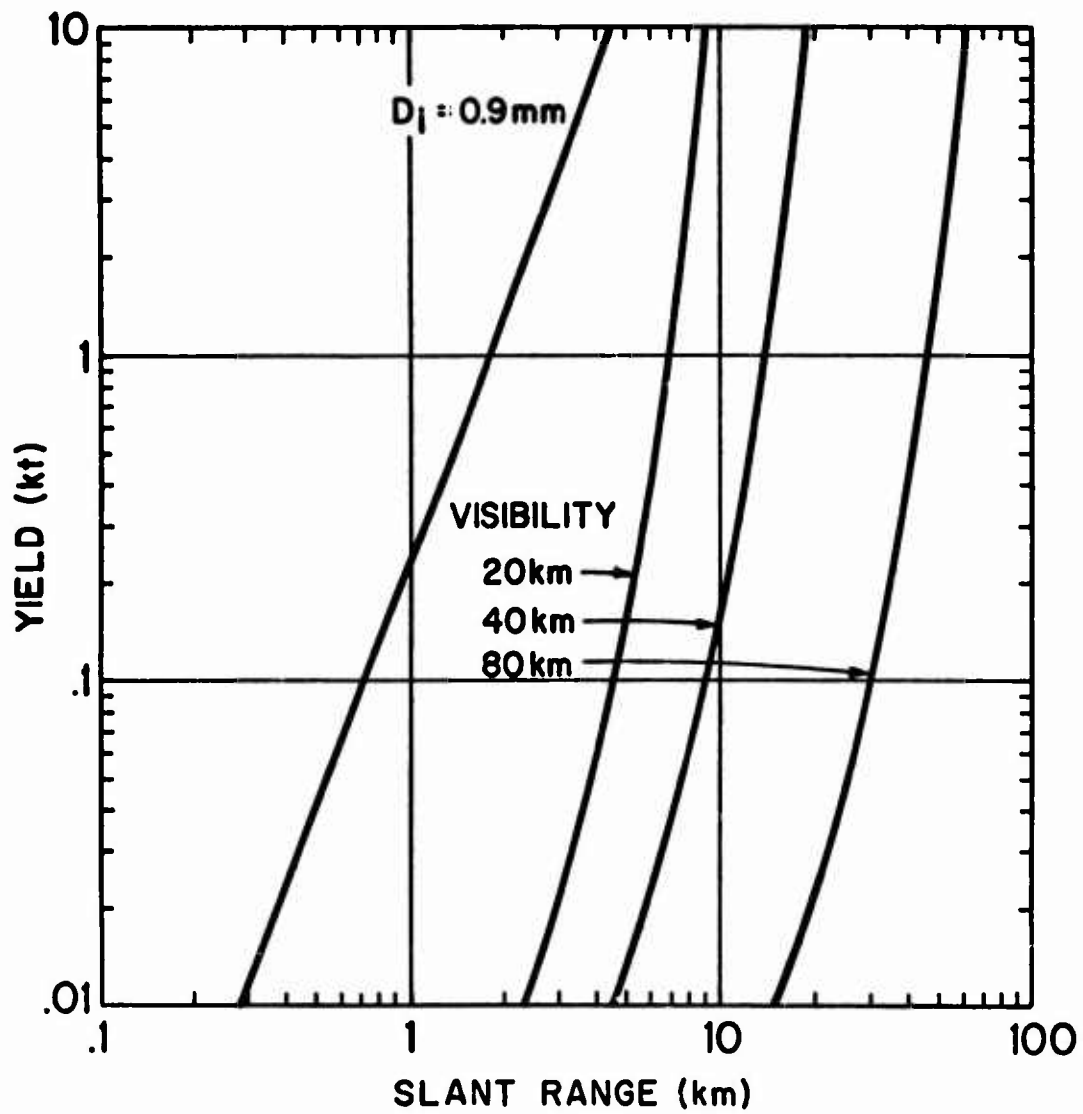
Fig. 10 Predicted distance for retinal exposure of 0.01 cal/cm^2 versus yield for
human eye protected by 2% fixed filter in bright daylight.
The D_i = 0.9 mm line shows the distance versus yield for a fireball
image diameter of 0.9 mm

RESISTANCE TO FLASH BLINDNESS

AND AIRCREW SELECTION

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SUMMARY

The resistance to dazzle in aircrew has been investigated.
Experiments using COMBERG's recording nyctometer have shown that the
time lag for return to a useful visual acuity (5/10) after exposure to
flash does not change with the subject's age, but is markedly long in
10% of aircrew tested.

The sensitivity to dazzle is therefore a criterion which should be
evaluated during the ophthalmologic part of aircrew physical
examinations.

Finally, the authors discuss efforts to increase dazzle resistance
by using anthocyanosides.

RESISTANCE TO FLASH BLINDNESS
AND AIRCREW SELECTION

A.Mercier and G.Perdriel

Apart from its photo-thermic action which can cause irreversible damage to the retina, an atomic flash creates severe dazzle at great distances and in all directions as a result of diverse reflections of the incident light flux.

The recovery of a degree of visual function sufficient for safety in the air is essential since it is accepted that for a pilot loss of useful vision for 5-10 seconds can have fatal consequences.

The use of protective goggles against atomic flash should prevent this retinal dazzle; but their use cannot be considered to offer complete protection. They are liable to permit sufficient penetration of incident light to cause loss of retinal adaptation. Other devices offer protection against only one flash, and during the period required for their replacement, a second explosion may take place. Finally, even the most advanced protective systems are liable to malfunction and we must also consider the occasional pilot who will neglect to wear his goggles, some of which are cumbersome and uncomfortable.

In our opinion, all the foregoing considerations call for an investigation of the various physiological parameters involved in flash blindness, and particularly for research into individual sensitivity to high-intensity light.

In aircrew, recovery from dazzle depends on several factors (intensity and duration of the flash; level of illumination in the cockpit; level of instrument panel illumination).

Hill and Chisum have provided some particularly interesting data on these different parameters.

Using the photo stimulator designed by J.Francois, we found that for a flash intensity of 150 joules, lasting 1.4 milliseconds, the *average* recovery time sufficient for reading flight instruments illuminated with the usual 3 nits of white light was 42 seconds. By raising the instrument illumination level to 150 nits, recovery time was reduced to 8 seconds. However, during this series of experiments, we were struck by the wide range of responses which, while following the same pattern, varied among different subjects. For instance, in the last experiments, individual recovery times ranged between 15 seconds and 4 seconds, for an average of 8 seconds. As a matter of fact, this scatter has recently been described by Ariaga-Cantallura, who studied visual photopic recovery after dazzle in 423 pilots aged 15-38 years. For a given and constant light intensity, the most frequent recovery times were found in two groups: one of 242 subjects with 7-18 seconds, the other of 95 subjects with 18-32 seconds.

Aubert, measuring visual scotopic recovery times after exposure to a light source of 10.8 picostilbs (log units) for 20 seconds, found an average of 5 minutes 37 seconds in 68 subjects, but with very marked individual variations.

Our study was concerned with the effect of dazzle on visual acuity. This is the essential criterion which permits the pilot to read his flight instruments.

Two procedures can be used for this purpose

- the study of the variation in visual acuity *during* exposure
- the determination of the recovery time to the minimum separable *after* exposure to a light source of known intensity.

The former method is of course of no interest for our purpose and we therefore settled for the latter one, feeling that it would be useful to determine recovery time after dazzle resulting in a visual acuity of 5/10 in subjects who normally have a discrimination faculty of 10/10.

The 5/10 level would appear to be the appropriate one, giving a borderline reliability for reading the flight instruments.

Inasmuch as several investigations have established the variations in this resistance as a function of age, we have tried to evaluate these possible effects in three categories of aircrew (40 subjects between 20 and 30 years of age; 40 between 31 and 40, and 40 between 41 and 50).

To eliminate any possibility of error in technique and to ensure perfectly comparable data, we used *Comberg's recording nyctometer*, which provides fully standardized stages of examination.

The experimental design for each subject is the following: the subject looks through two openings into an *Ulbricht sphere*. Pressing a button initiates the experimental sequence.

(a) During three minutes, the subject is dazzled by a light source of 7,000 apostilbs (about 1550 nits). This intensity is obviously below that of an atomic flash; but the difference is partially compensated for by longer exposure time.

(b) The light source is extinguished and a table of feebly illuminated (0.5 apostilb) test type becomes visible. This level of illumination is roughly one twentieth of that of a barely illuminated instrument panel.

(c) The examiner records, on a roll of paper attached to a drum, the visual acuity levels regained by the subject as time progresses.

RESULTS

By studying the individual tracings, we found the following for the three categories of subjects described above:

- the average reaction levels
- higher levels correspond with better recovery
- lower levels indicate greater sensitivity to dazzle.

These different results were compared with normally expected variations.

We arrived therefore at the following conclusions:

1. The mean value of dazzle resistance varies very little as a function of age. Only the 41-50 age group shows a tendency to slightly impaired responses (Fig.1). In addition, we find that even if visual acuity returns to 5/1- after 120 seconds, only 65 seconds are required to attain a minimum separable of 4/10.

2. Regardless of the age category, it can be stated that:
    - normal recuperation takes place in 60% of subjects
    - excellent recuperation takes place in 30% of subjects
    - clearly insufficient recuperation takes place in 10% of subjects (Fig.2).

This poor dazzle resistance is characterized by a time lapse of 60 seconds before reaching an acuity of 1/10 and inability to reach more than 3/10 at 120 seconds.

It would appear useful therefore to introduce into the aircrew selection physical examination a test for visual recuperation time after dazzle. This recommendation is supported by the fact that one out of every ten aircrew shows a deficiency in this regard.

Even in qualified pilots it would be equally useful to identify those with the least sensitivity to dazzle.

In another series of experiments we studied the possible influence of anthocyano-sides upon dazzle resistance, proceeding from the promising results obtained with this substance in the regeneration of rhodopsin.

This research was performed by using one particular capability of the *Mesoptometer*. This consists of measuring the speed of visual readaptation after dazzle (intensity of light source equal to that of an automobile headlight, placed at an angle of two degrees from the fixation point). The subject is dazzled for 10 seconds and after switching off the dazzle source, the recovery time is measured to the level of acuity previously determined in dusk conditions at 0.1 apostilbs.

31 subjects underwent this test before and after taking five anthocyanoside tablets per day for five days. Each tablet contains 0.1 grams of the active product and 0.005 grams of Beta caroteine.

The following results were obtained:

    - 14 subjects showed no difference in recovery time which, for a given acuity, was 3 seconds
    - 12 subjects demonstrated improved dazzle resistance in that recovery time to normal visual acuity was reduced by 1 to 2 seconds
    - 5 subjects paradoxically showed a reduction of their visual efficiency (prolongation of response time by 1 to 2 seconds).

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To date this is a small experimental sample and it is difficult to ascribe any beneficial action to the product in view of the controversial results.

We plan to continue this research by initiating a statistical study in a larger number of subjects, some of whom would take placebos and other anthocyanosides. A statistical study would therefore provide more objective results.

In conclusion, we feel that sensitivity to dazzle should be determined in pilots who are likely to have to operate in an atomic strategic environment, and that recovery time appears to be the best criterion for evaluating their visual capabilities in case of exposure to atomic flashes.

Our research activities will be orientated towards the improvement of visual function after dazzle, using certain compounds capable of speeding up the recovery of visual purple and of the pigments in the photopic receptors.
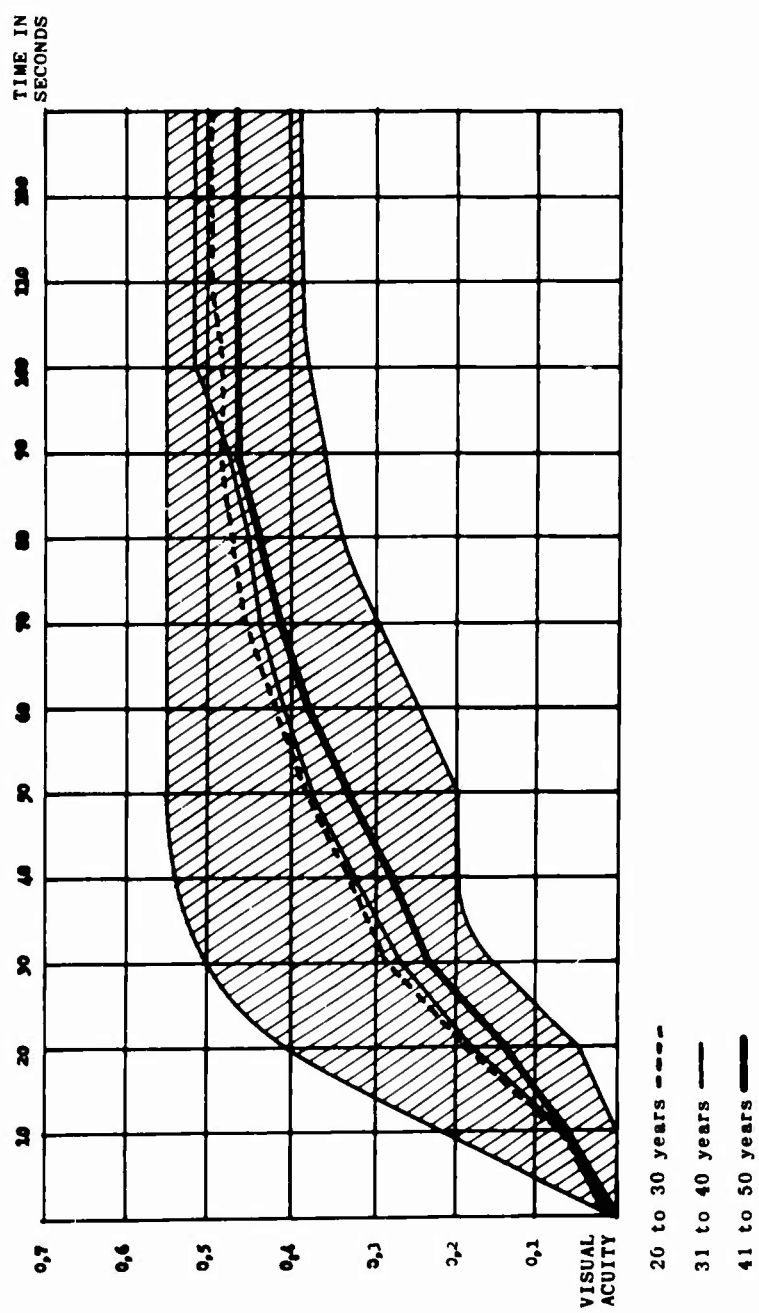
Fig.1 Recovery of visual acuity after dazzle (7000 apostilb) as a function of age
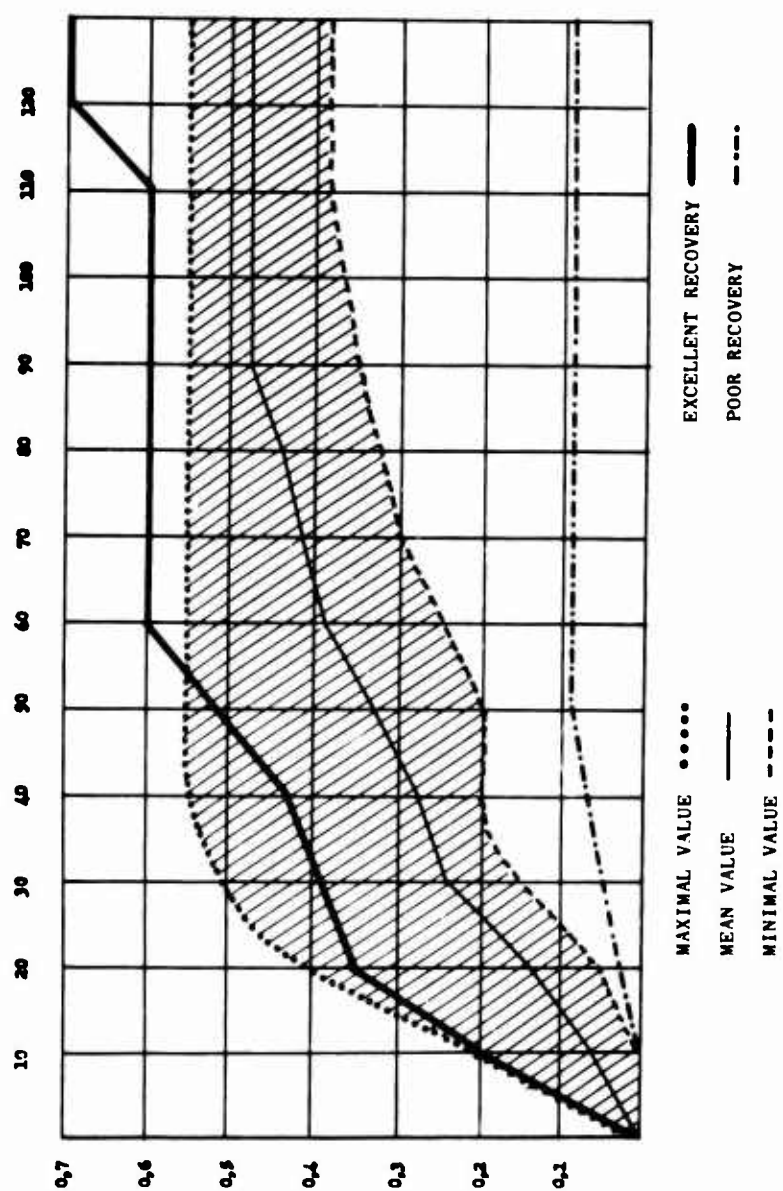
Fig. 2 Recovery of visual acuity after dazzle (7000 apostilb) in flying personnel over 40 years of age

APPENDIX

Units of Light Measurement
(Based on B.S. 233 1953)

Term	*Definition*
Lumen	The unit of luminous flux. The flux emitted in unit solid angle of one steradian by a point source having a uniform intensity of one candela. (C.I.E.) Abbreviation: lm.
Lux	A unit of illumination of one lumen per square metre. (C.I.E.) Abbreviation: lx.
Lumen per square foot Foot-candle	A unit of illumination. An illumination of one lumen per square foot. Abbreviation: lm/ft^2 or lm/sq.ft. NOTE: One lm/ft^2 equals 10.764 lux.
Candela	The unit of luminous intensity. It is of magnitude such that the luminance of a full radiator at the temperature of solidification of platinum is 60 units of luminous intensity per square centimetre. (C.I.E.) Abbreviation: cd.
Candle-power	The light-radiating capacity of a source in a given direction, in terms of the luminous intensity expressed in candelas.
Nit	A unit of luminance. A luminance of one candela per square metre. (C.I.E.) Abbreviation: nt.
Stilb	A unit of luminance. A luminance of one candela per square centimetre. Abbreviation: sb.
Apostilb	A unit of luminance. The luminance of a uniform diffuser emitting one lumen per square metre. Abbreviation: asb.
Lambert	A unit of luminance. The luminance of a uniform diffuser emitting one lumen per square centimetre. The milli-lambert is one thousandth of a lambert.
Foot-lambert Equivalent Foot-candle, deprecated	A unit of luminance. The luminance of a uniform diffuser emitting one lumen per square foot. Abbreviation: ft-L.

UNITS OF LUMINANCE

	cd/m^2	cd/cm^2	cd/ft^2	ft-L	asb.
Candelas per sq.m. (nits)	1	0.000 1	0.092 9	0.291 9	3.141 6
Candelas per sq.cm. (stilbs)	10 000	1	929	2 919	31 416
Candelas per sq.ft.	10.76	0.001 076	1	3.141 6	33.82
Foot-lamberts	3.426	0.000 342 6	0.318 3	1	10.764
Apostilbs (asb)	0.318 3	0.000 031 83	0.029 57	0.092 9	1

1 Foot-lambert = 1 lumen/929 cm^2 $\doteq$ 1 Milli-lambert